NASA Snow Mapper Reaps Big Benefits for California: the Airborne Snow Observatory

Thomas Painter, **NASA Jet Propulsion Laboratory, Pasadena, CA**
Bruce McGurk, **McGurk Hydrologic Associates, Orinda, CA**
Jessica Lundquist, **University of Washington, Seattle**
Bradley Doorn, **NASA Headquarters, Washington DC**

Jet Propulsion Laboratory
California Institute of Technology

Western Water Assessment

McGurk Hydrologic

NSIDC
National Snow and Ice Data Center

Outline

Overview of Airborne Snow Observatory

2013 Demonstration Mission

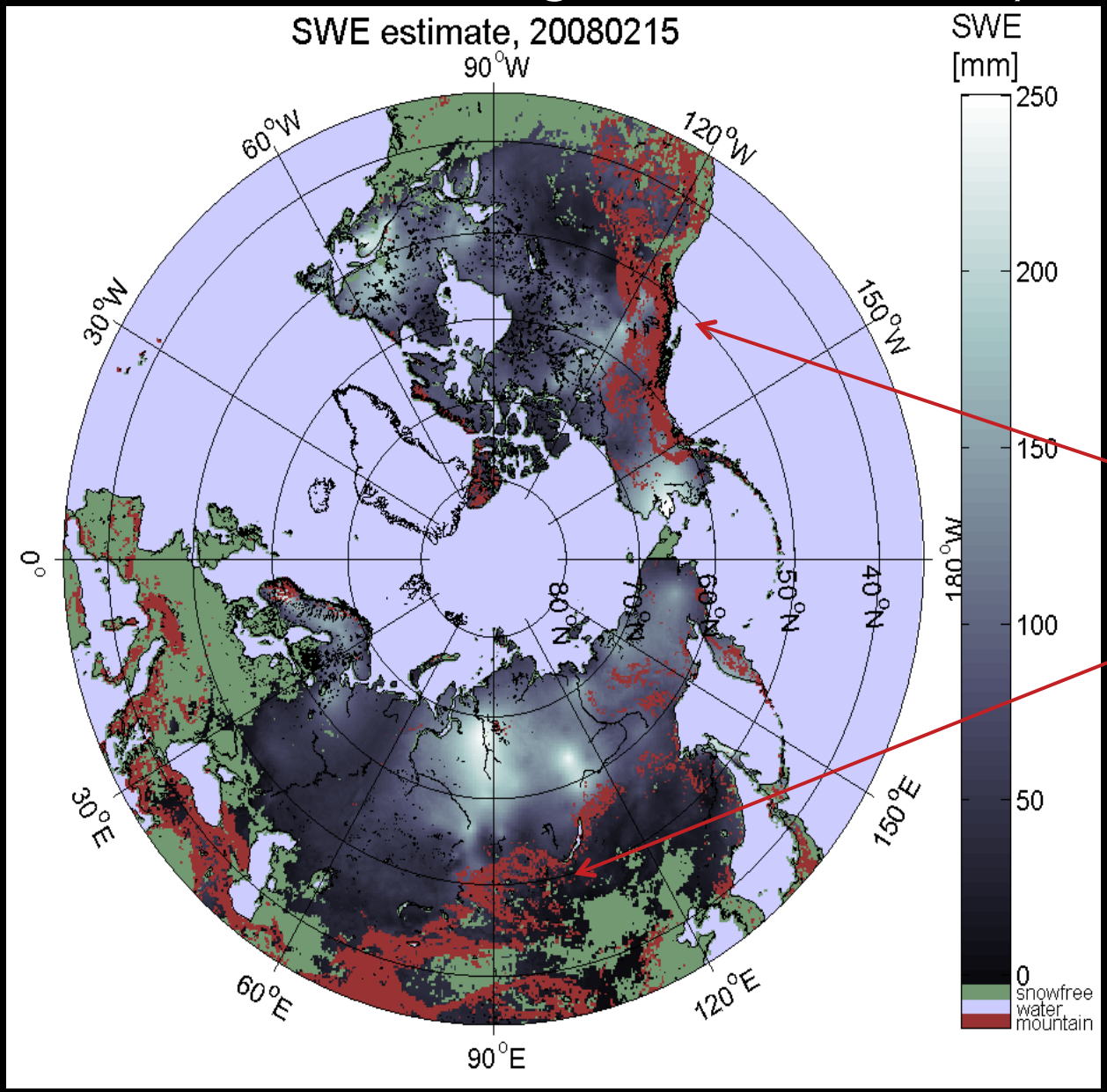
Implementation in reservoir operations and management

Implications for snow hydrology and glaciology, NASA directions

Panel

- **Thomas H. Painter,** Scientist, NASA Jet Propulsion Laboratory and Principal Investigator of the Airborne Snow Observatory
- **Bruce McGurk**, Consultant and former manager of Hetch Hetchy Operation, City of San Francisco
- **Jessica Lundquist**, Associate Professor, Dept of Civil and Environ Engineering, U of Washington
- **Bradley Doorn**, Applied Sciences program manager for Water Resources, NASA Headquarters

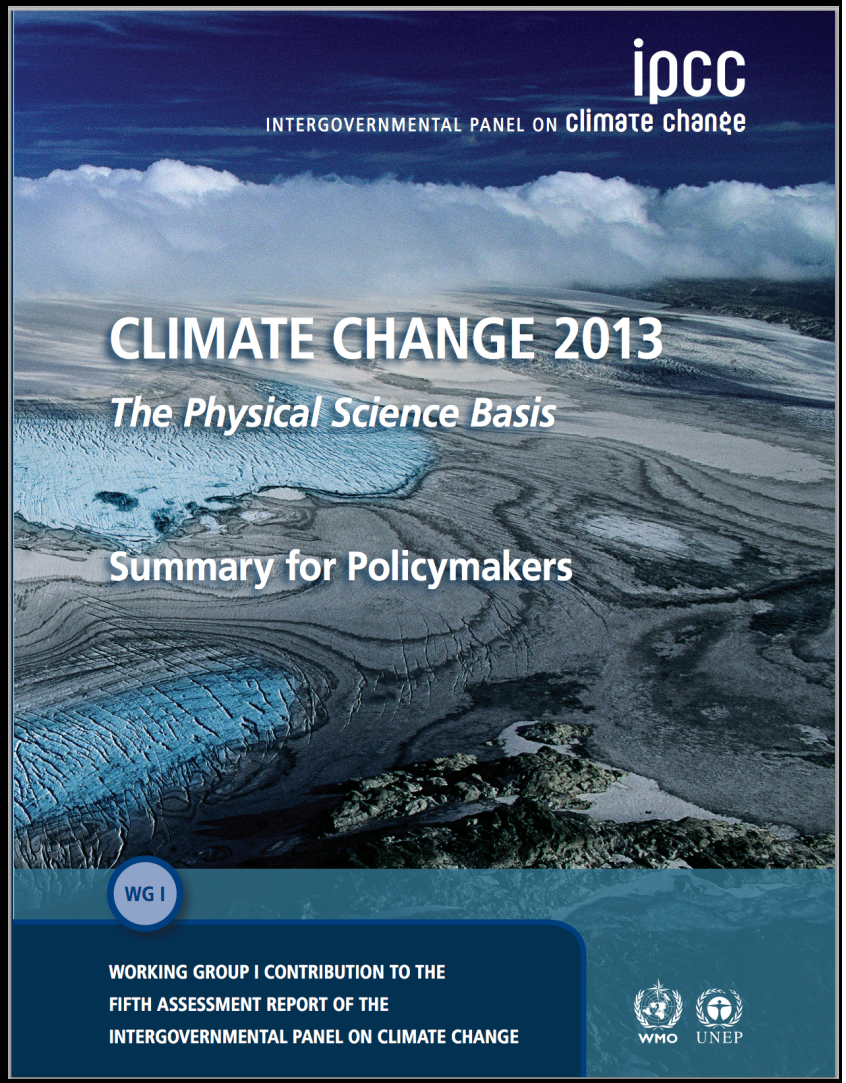
Best remote sensing of snow entirely omits mountains



Mountains masked out

Who suffers from bad snow information?

- Climate change scientists
- Glaciologists
- Hydrologists
- Carbon cycle scientists
- Atmospheric scientists



Snowmelt Runoff Forecasting

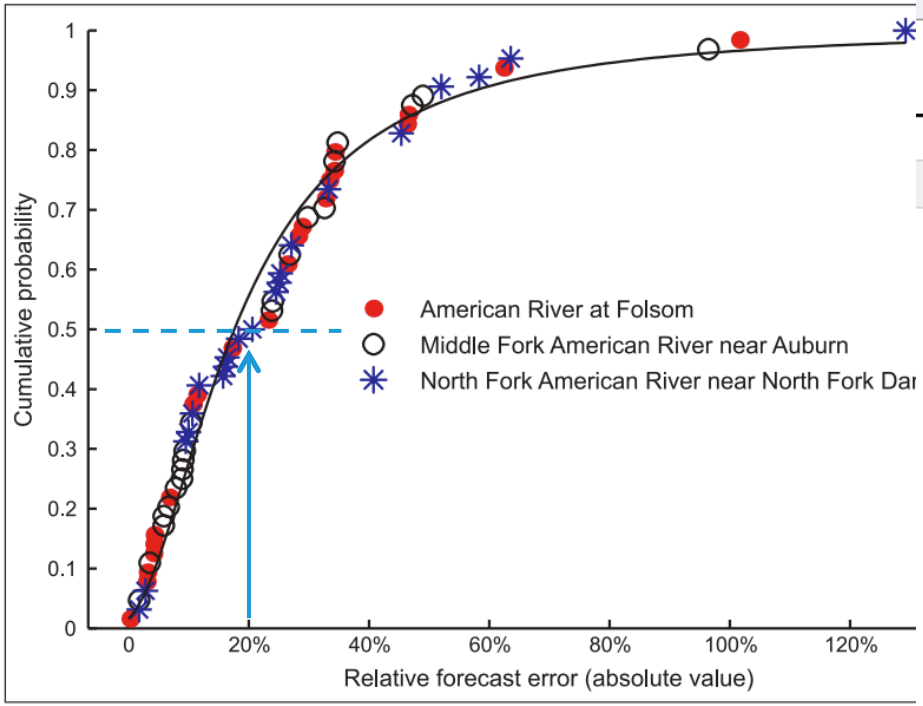


Fig. 1. Errors in the 1 April forecast for April–July runoff in the American River, 1990–2011, base on gauges at Auburn and Folsom, in California. Note that the median error is 18% and the 80t percentile (1 year in 5) error is 39%. The plot was generated from information from the Califo Data Exchange Center.

Dozier 2012

In 1 of 5 years, forecast errors are greater than 40%. Half the time, they are greater than 20%. These come from poor data and poorly constrained science.

In California, Reading the Snow to Tell the Future for the Water Supply

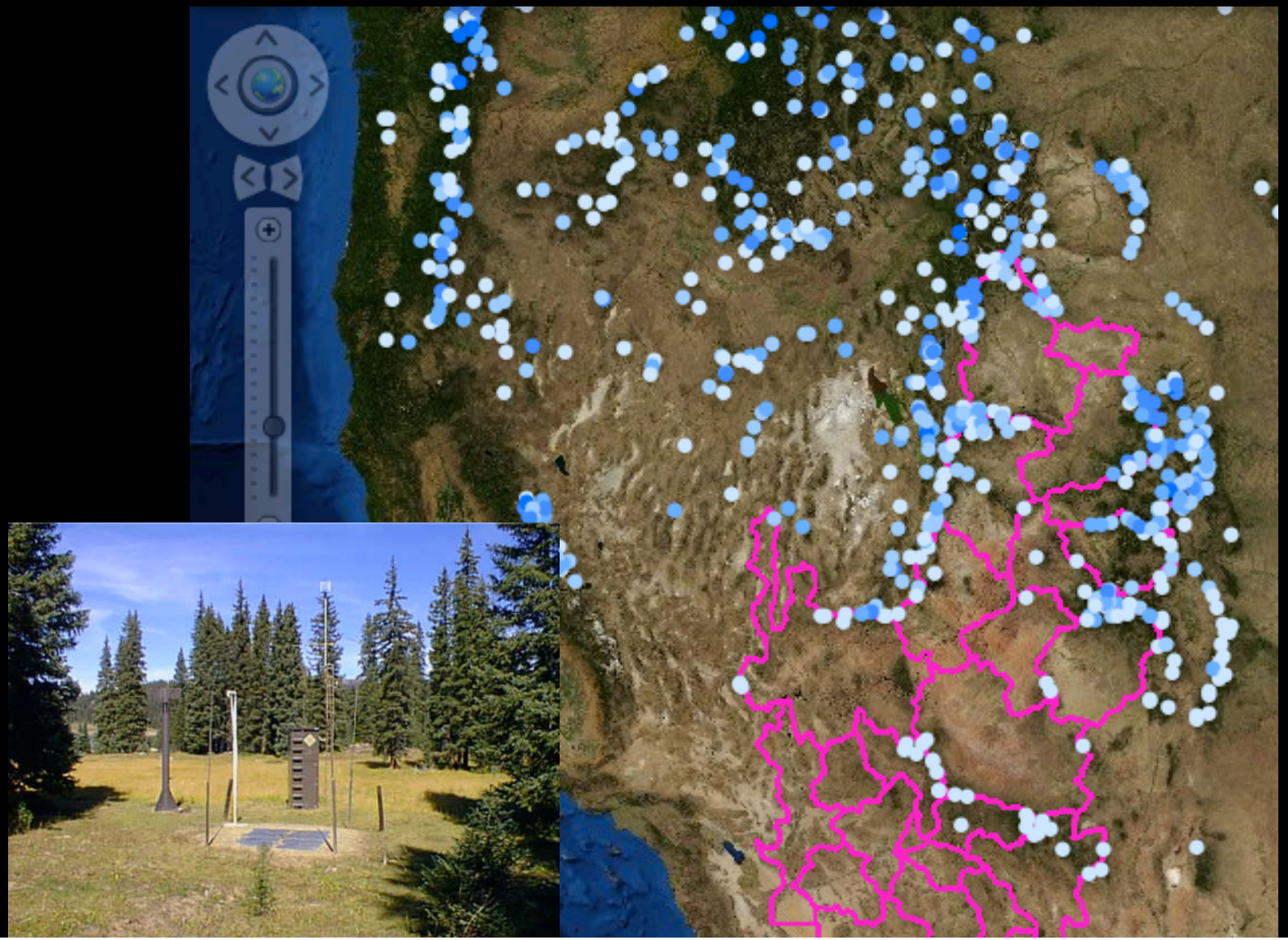
Max Whittaker for The New York

Frank Gehrke, center, has led snowpack surveys in California for a quarter-century. The state's multibillion-dollar agricultural industry pays close attention.

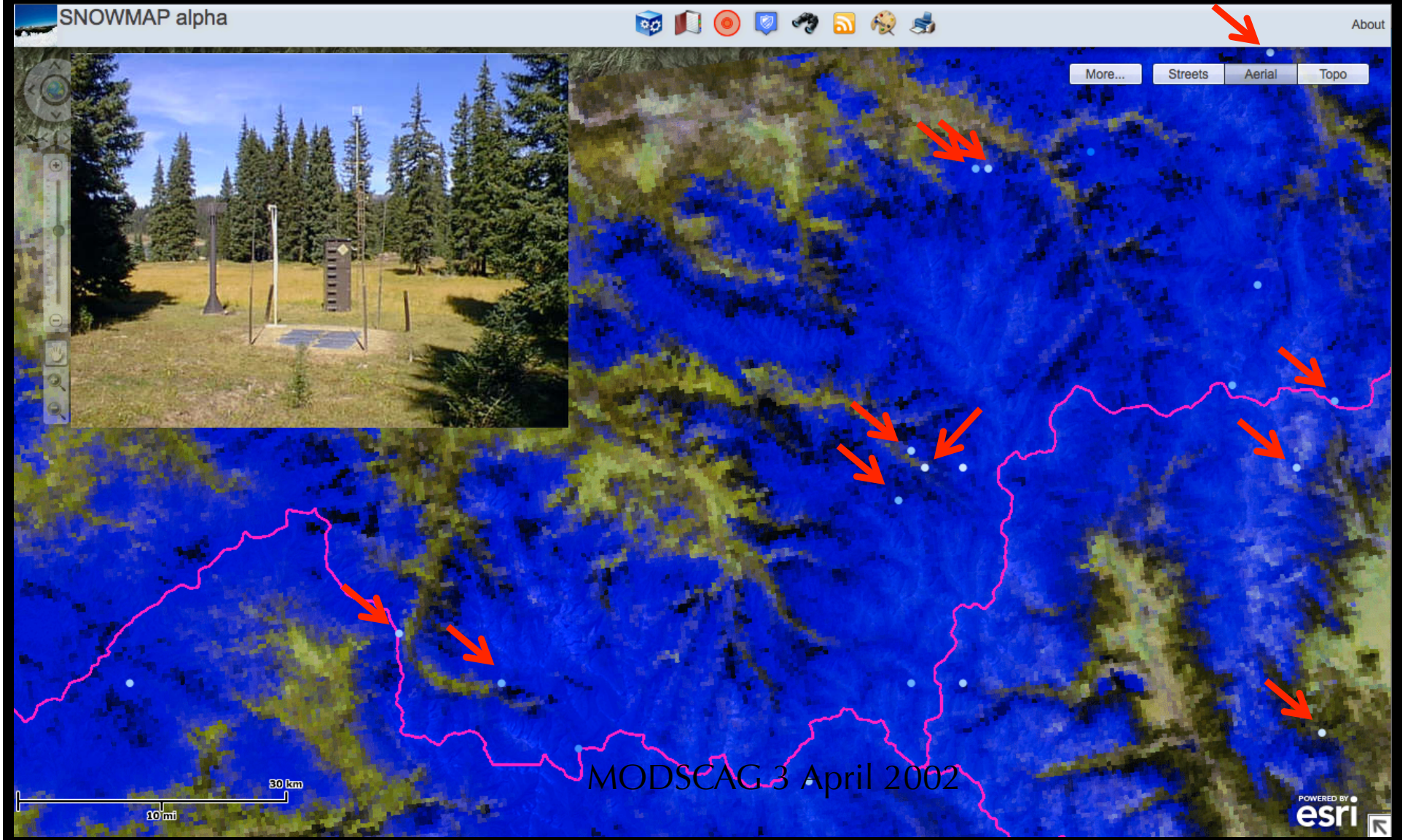
By NORIMITSU ONISHI
Published: February 7, 2013

Manual measurement of SWE (snow water equivalent), started in the Sierra Nevada in 1910

Seems like good coverage?



When the snow pillows melt, we're blind



MODSCAG 3 April 2002

ASO Technology

Imaging Spectrometer
0.35-1.05 μ m
2 m spatial resolution from 4000 AGL

Albedo

Uncertainty < 2%

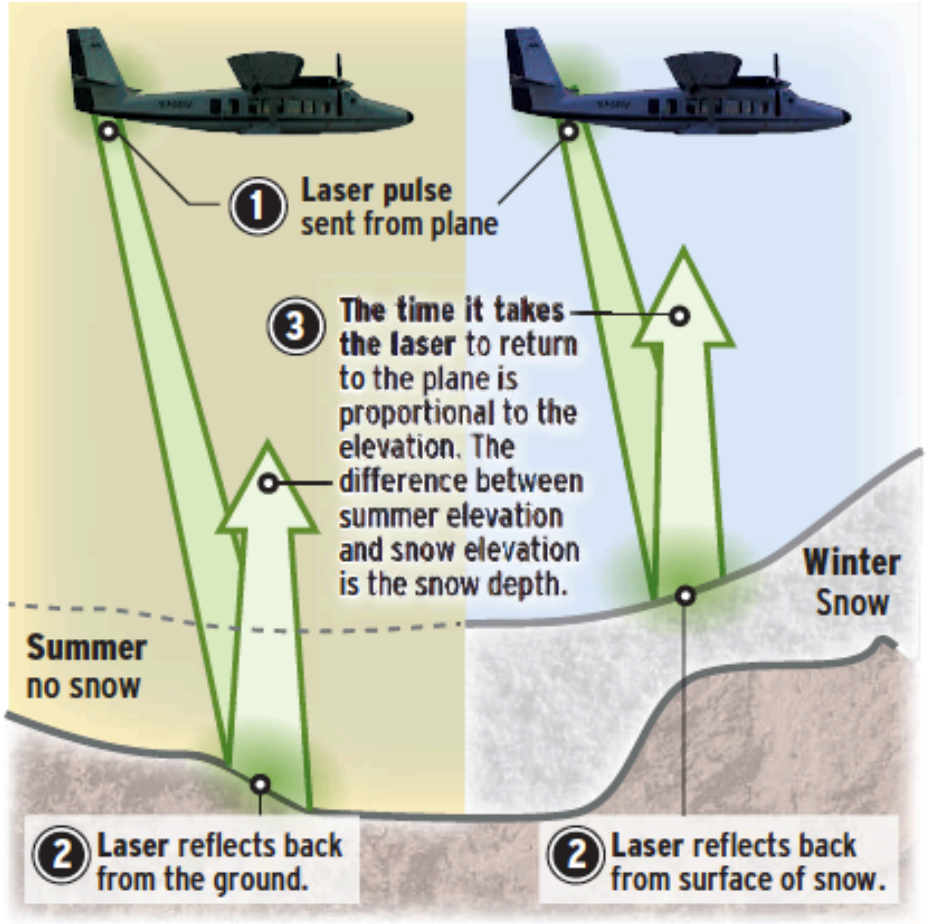
Snow Water Equivalent

Uncertainty < 5 cm

3D Scanning LiDAR
1064 nm
1 m spatial resolution

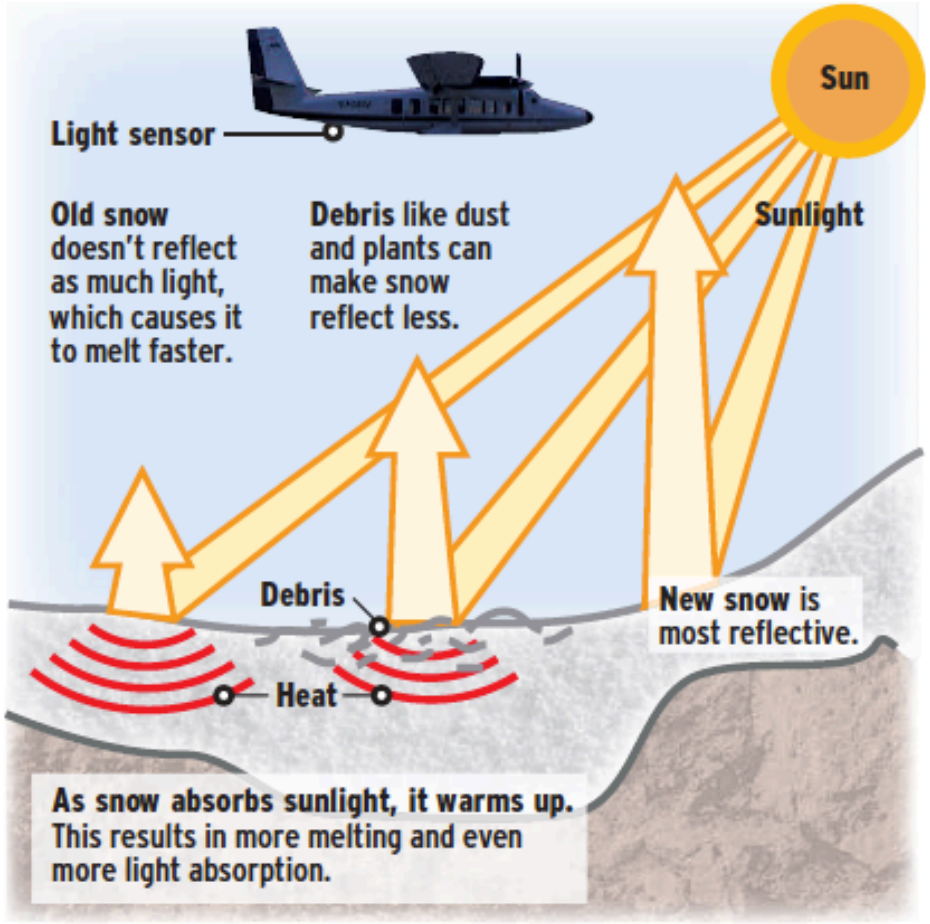
How much snow?

Using laser radar, known as Lidar, researchers measure the depth of snowpack in California.



How will it melt?

With an advanced light sensor, scientists measure snow's reflectivity – an indicator of how it will melt.



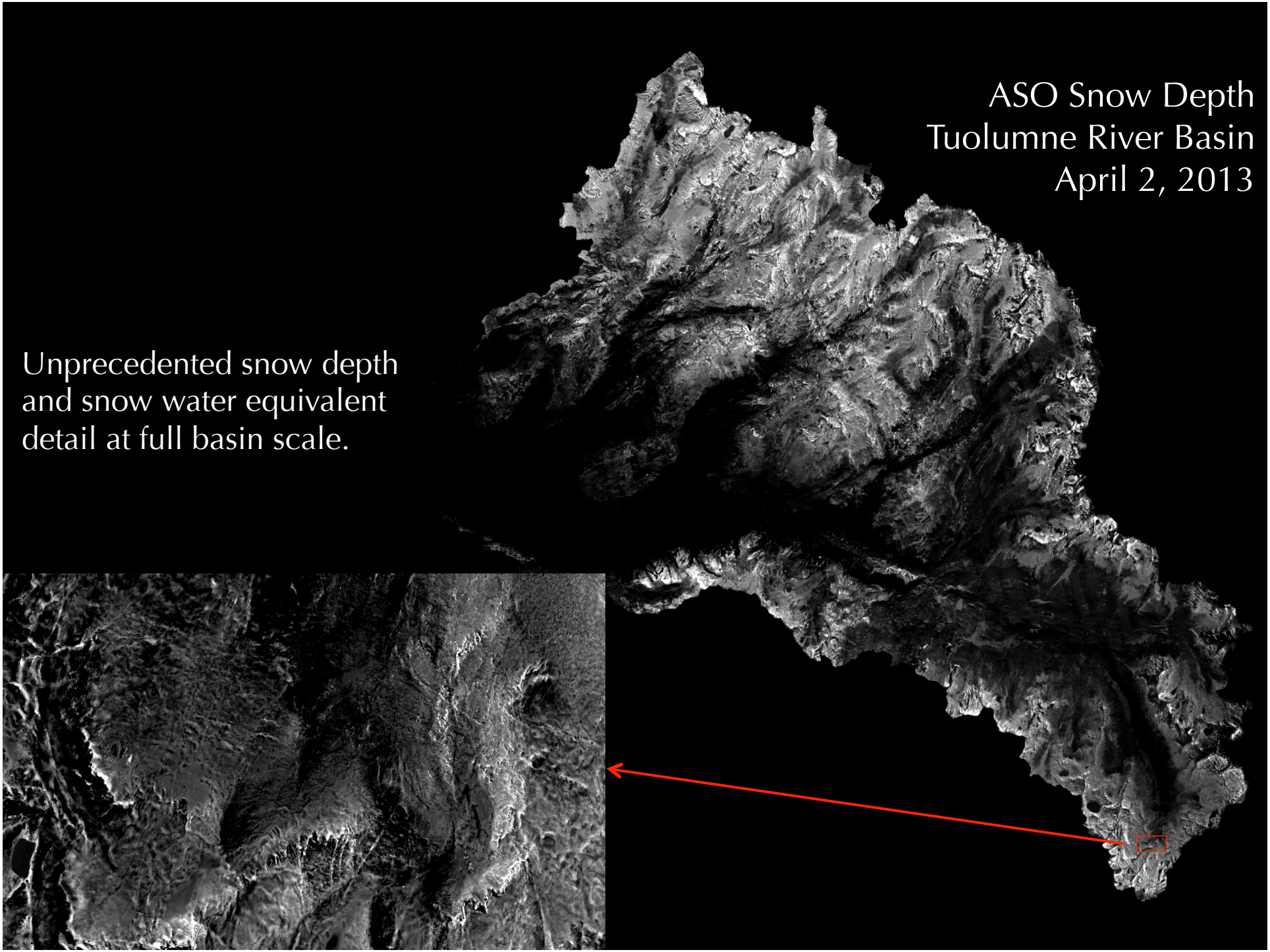
Sources: Thomas Painter, Frank Gehrke, Optech Inc.

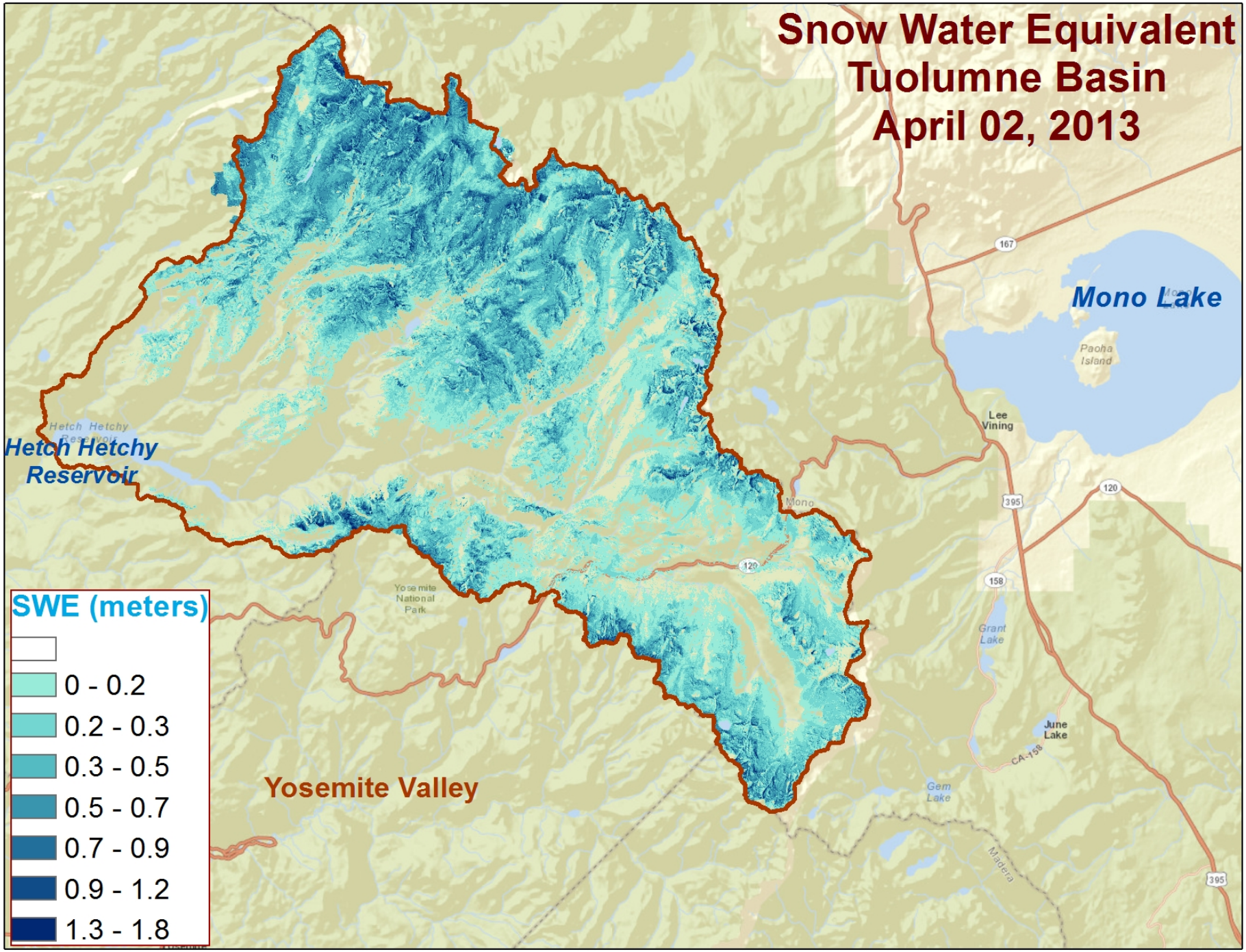
Maxwell Henderson / The Register

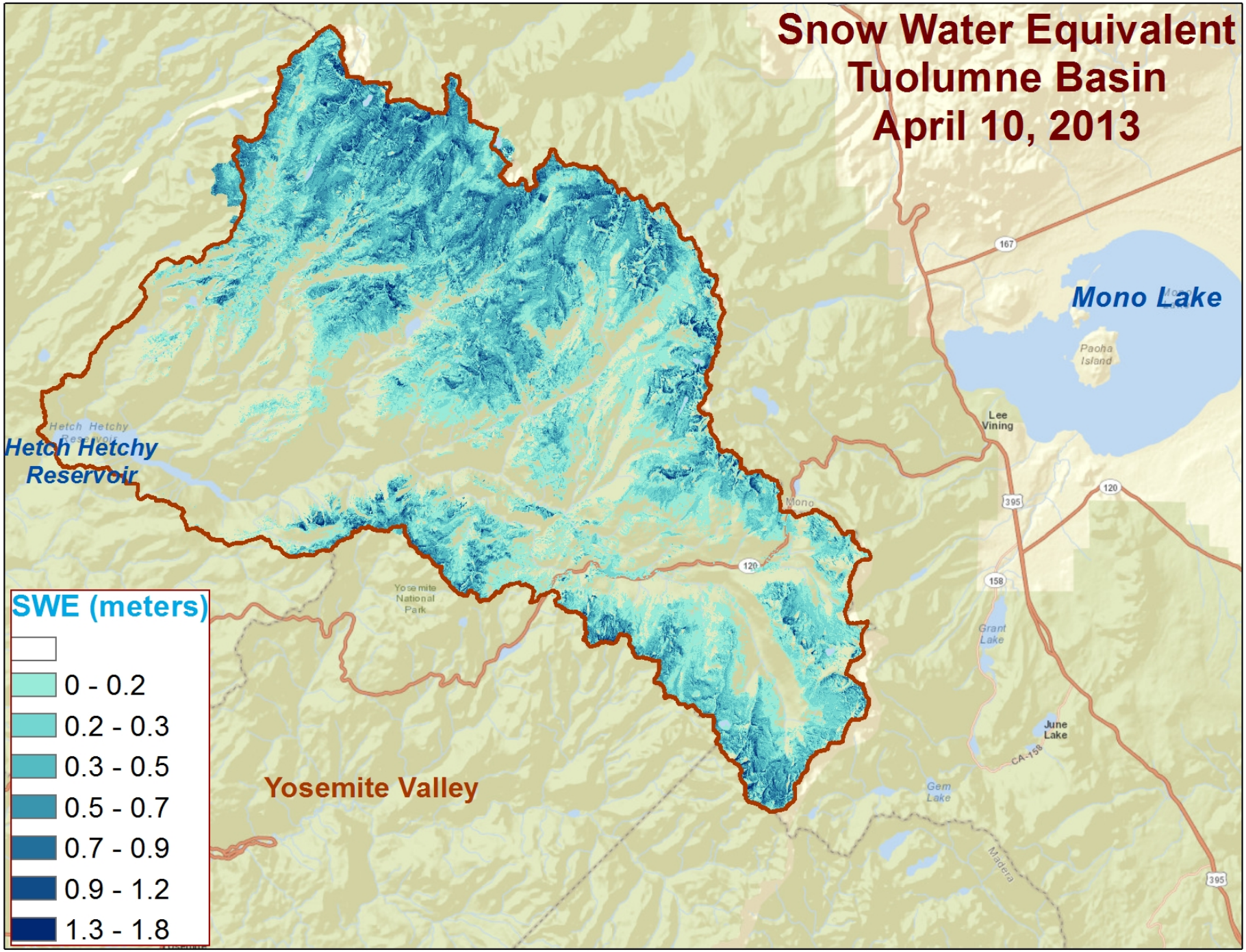
A natural color image of Mt. Lyell, highest

New methods of measuring a crucial source of water increase accuracy as climate change dries out the mountains.

ASO Demonstration Mission 2013


ASO Snow Depth
Tuolumne River Basin
April 2, 2013
Unprecedented snow depth
and snow water equivalent
detail at full basin scale.


Snow Water Equivalent
Tuolumne Basin
April 02, 2013
Mono Lake
Paoha Island
Lee Vining
Hetch Hetchy Reservoir
Mono
Yosemite National Park
Yosemite Valley
Grant Lake
June Lake
Gem Lake
Madera
CA-158
167
395
120
158
SWE (meters)
0 - 0.2
0.2 - 0.3
0.3 - 0.5
0.5 - 0.7
0.7 - 0.9
0.9 - 1.2
1.3 - 1.8


Snow Water Equivalent
Tuolumne Basin
April 10, 2013
Mono Lake
Paoha Island
Lee Vining
Hetch Hetchy Reservoir
Yosemite National Park
Yosemite Valley
Mono
Grant Lake
June Lake
Gem Lake
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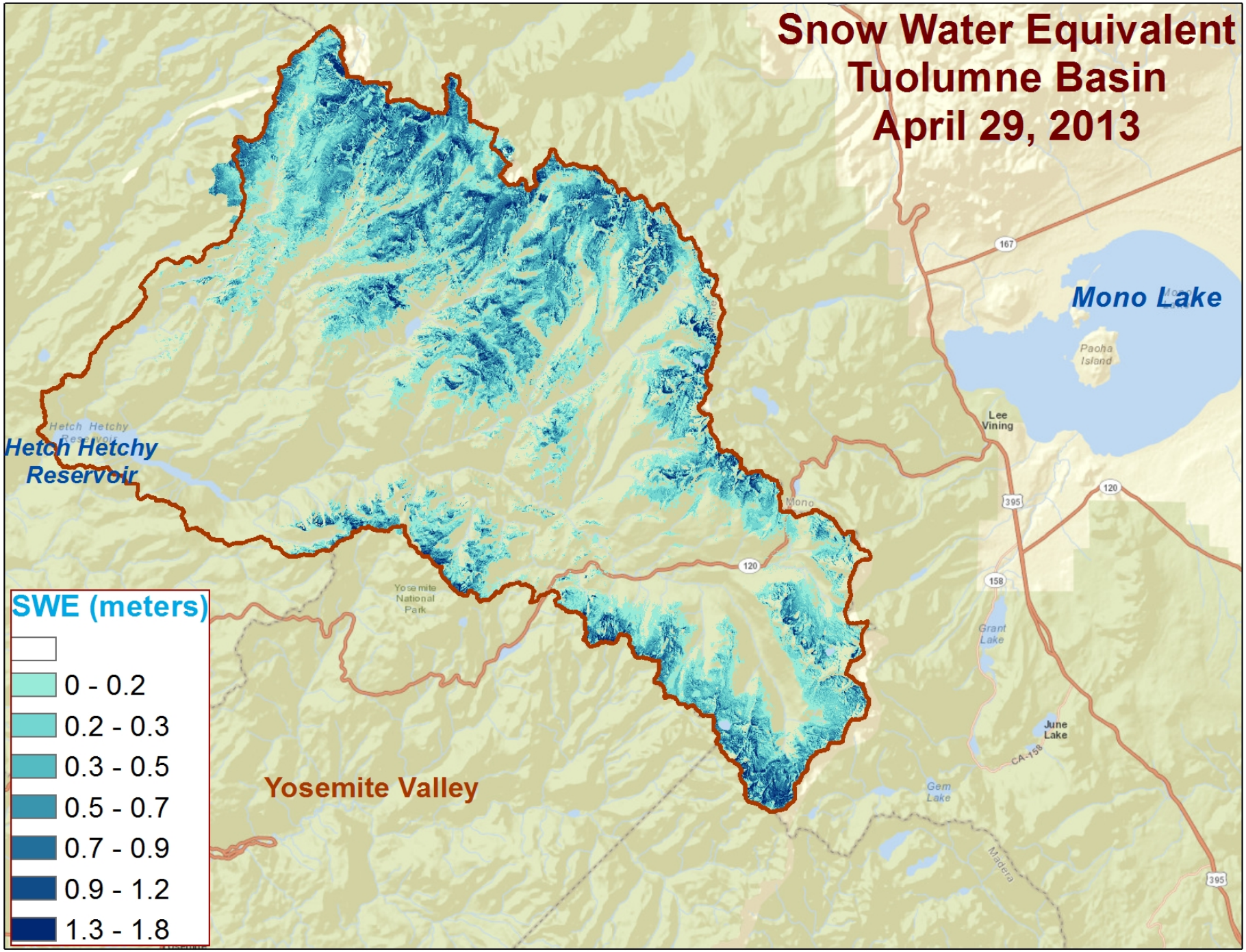
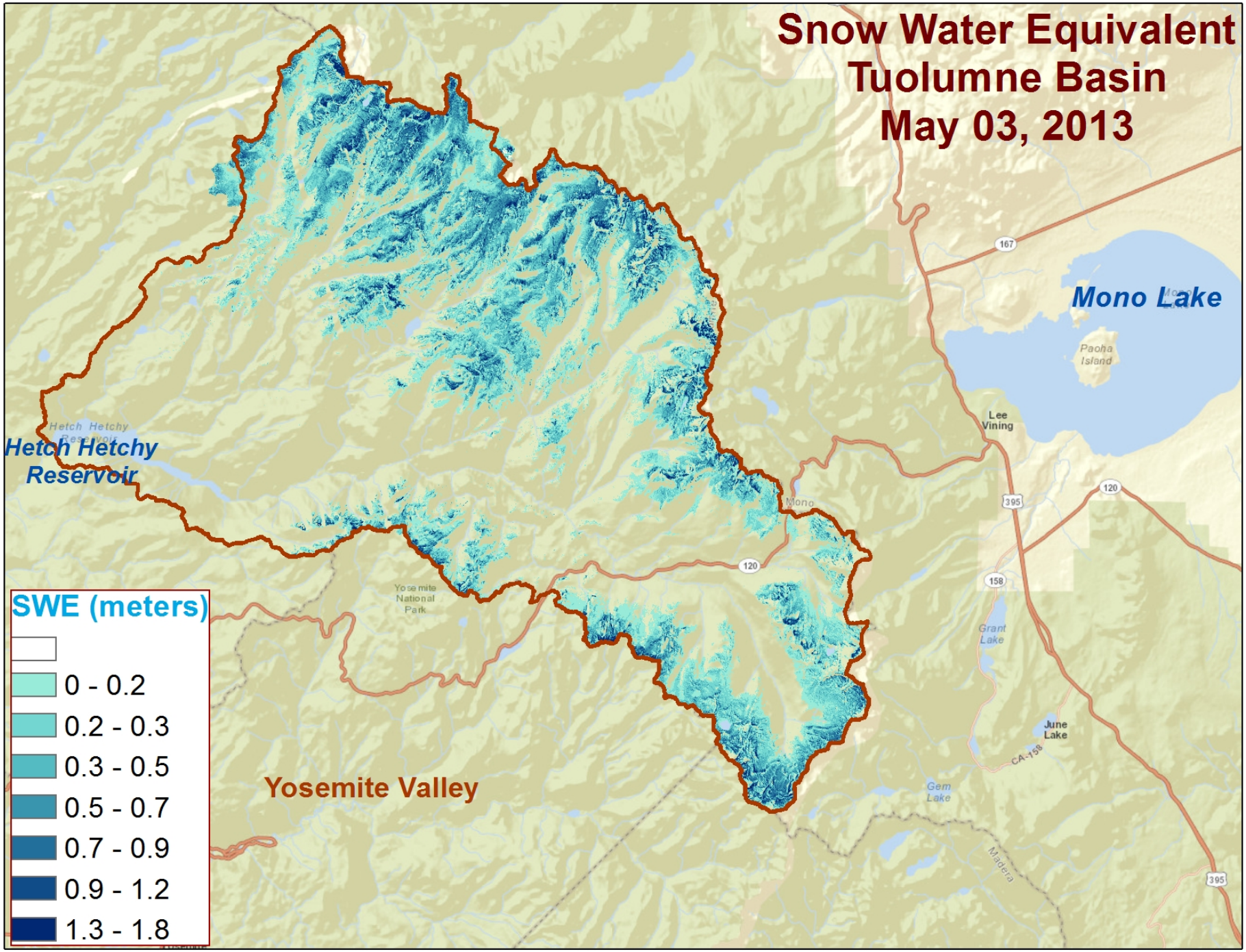

Snow Water Equivalent
Tuolumne Basin
April 29, 2013
Mono Lake
Paoha Island
Lee Vining
Hetch Hetchy Reservoir
Mono
Yosemite National Park
Grant Lake
June Lake
Gem Lake
Yosemite Valley
Madera
SWE (meters)
0 - 0.2
0.2 - 0.3
0.3 - 0.5
0.5 - 0.7
0.7 - 0.9
0.9 - 1.2
1.3 - 1.8


Snow Water Equivalent
Tuolumne Basin
May 03, 2013
Mono Lake
Paoha Island
Lee Vining
Hetch Hetchy Reservoir
Mono
Yosemite National Park
Grant Lake
June Lake
Gem Lake
Madera
Yosemite Valley
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CA-158
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0.2 - 0.3
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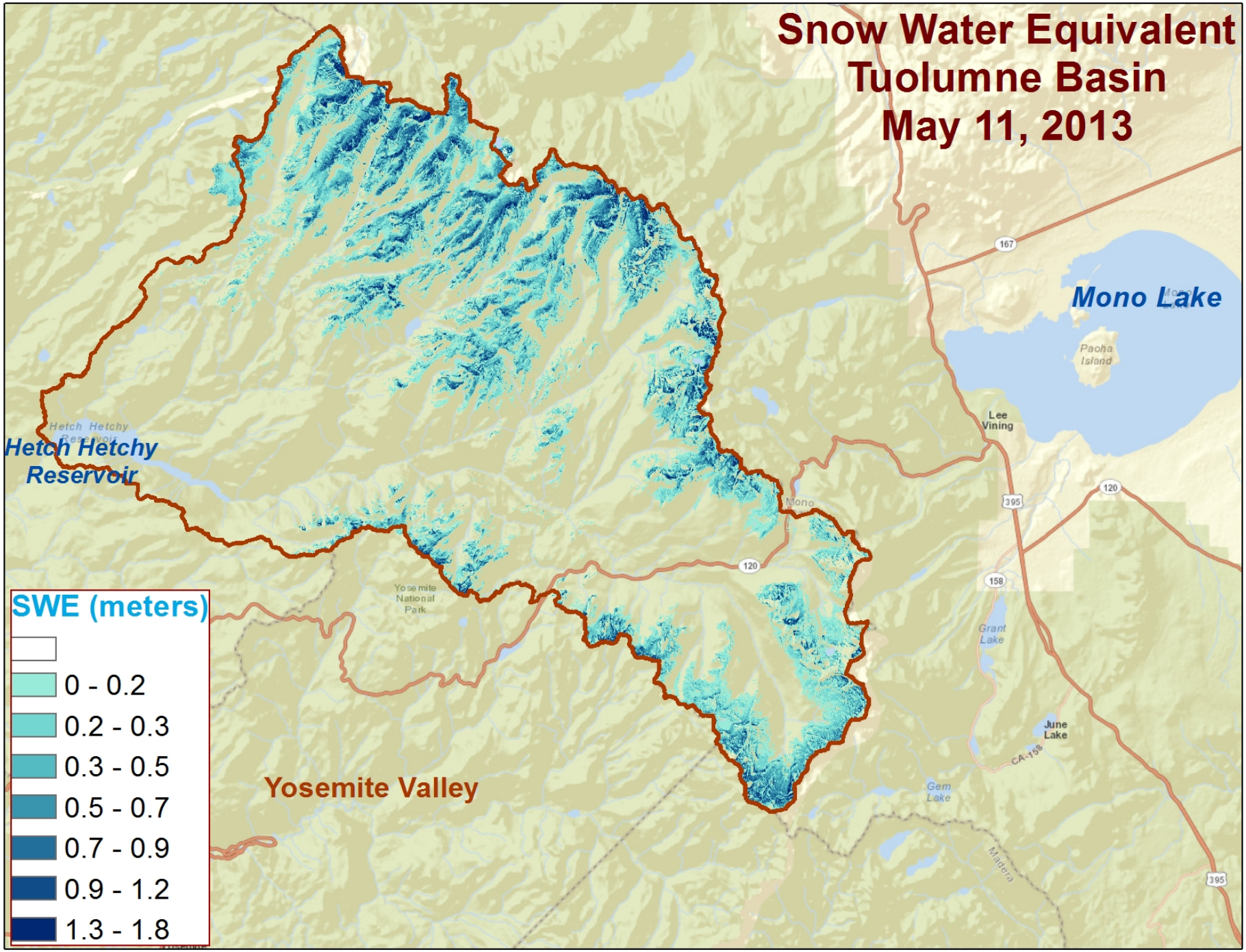
0.5 - 0.7
0.7 - 0.9
0.9 - 1.2
1.3 - 1.8


Snow Water Equivalent
Tuolumne Basin
May 11, 2013
Mono Lake
Paoha Island
Lee Vining
Hetch Hetchy Reservoir
Mono
Yosemite National Park
Yosemite Valley
Grant Lake
June Lake
Gem Lake
Madera
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SWE (meters)
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0.2 - 0.3
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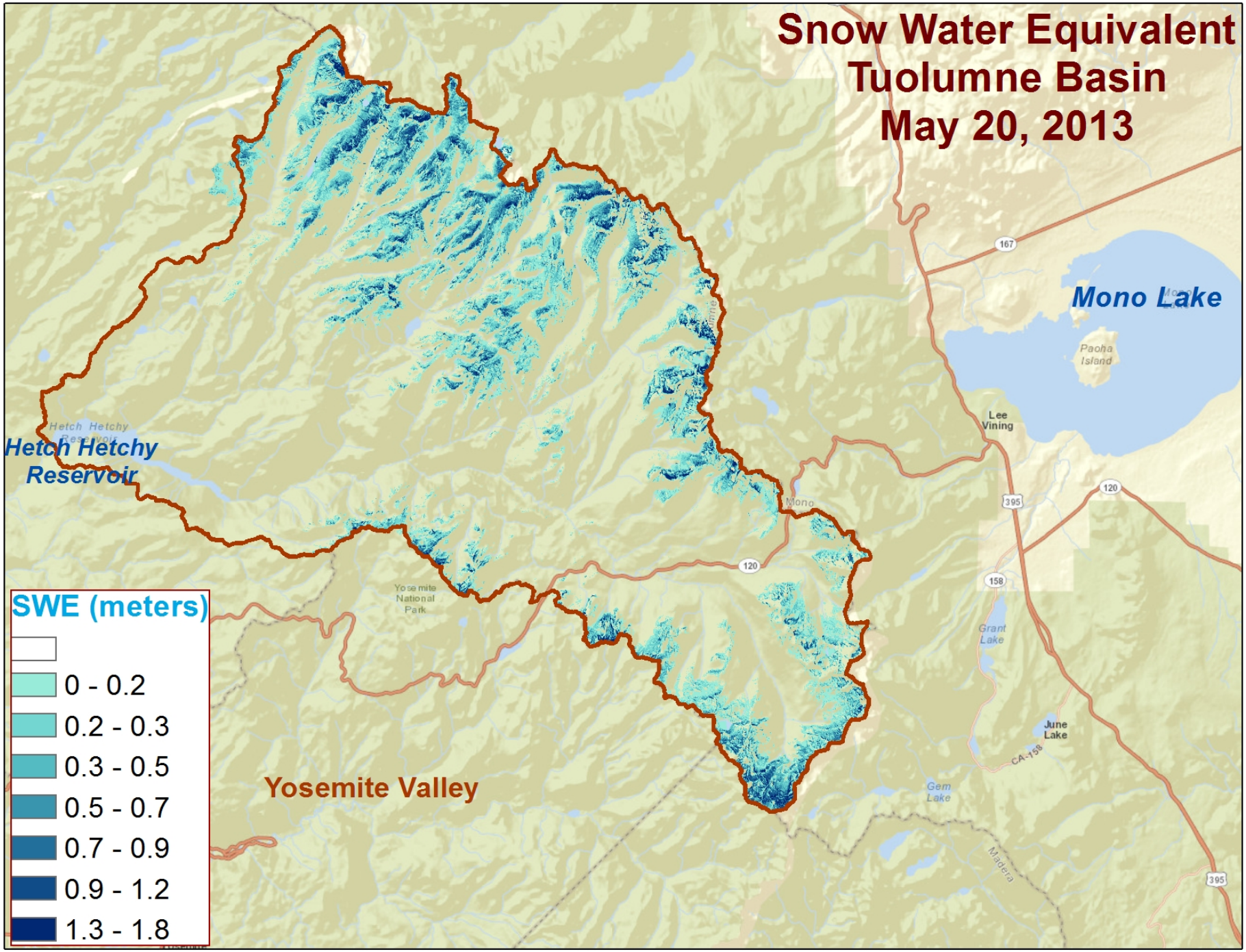
0.5 - 0.7
0.7 - 0.9
0.9 - 1.2
1.3 - 1.8


Snow Water Equivalent
Tuolumne Basin
May 20, 2013
Mono Lake
Paoha Island
Lee Vining
Hetch Hetchy Reservoir
Mono
Yosemite National Park
Grant Lake
June Lake
Gem Lake
Madera
Yosemite Valley
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CA-158
SWE (meters)
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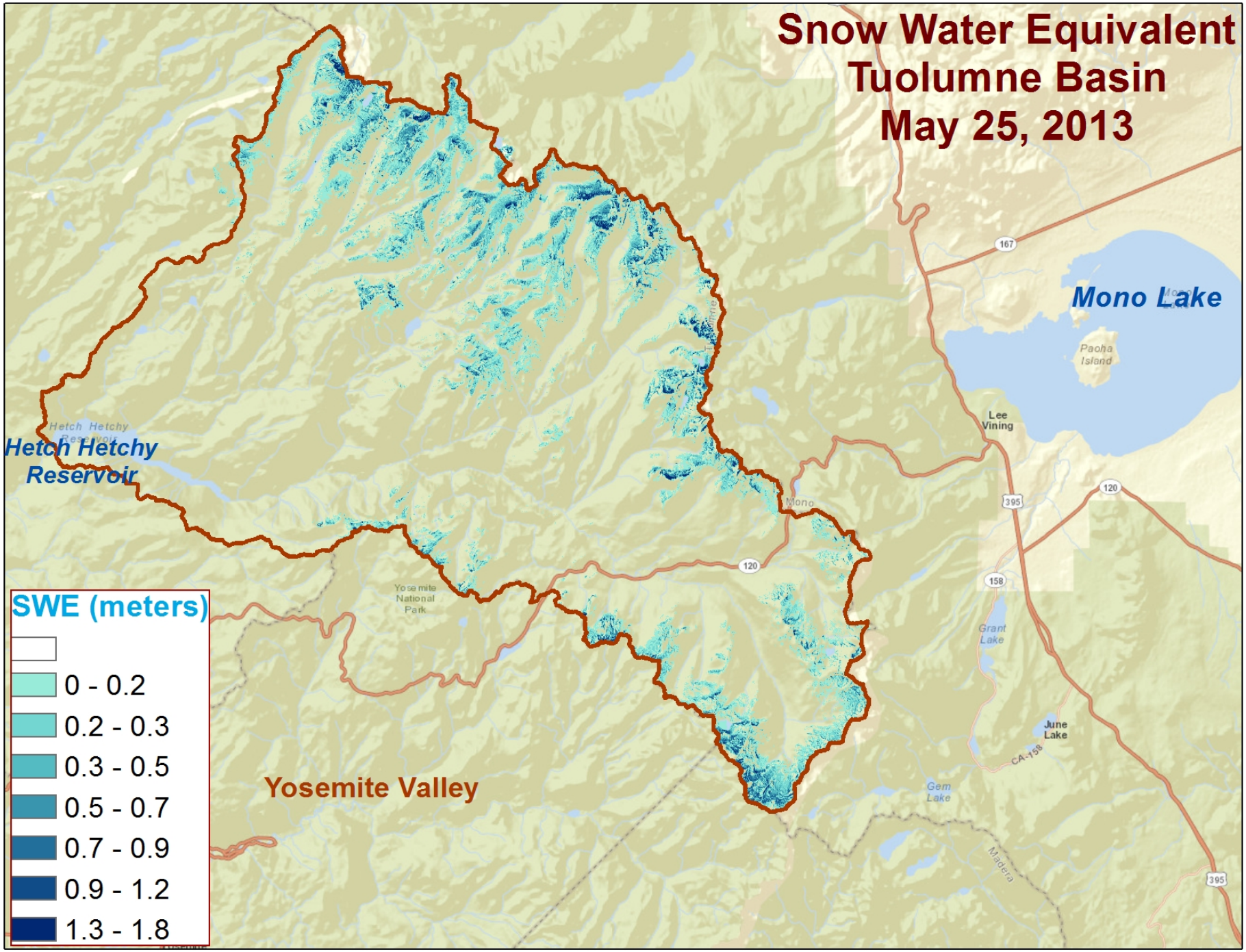
0.5 - 0.7
0.7 - 0.9
0.9 - 1.2
1.3 - 1.8


Snow Water Equivalent
Tuolumne Basin
May 25, 2013
Mono Lake
Hetch Hetchy Reservoir
Yosemite Valley
SWE (meters)
0 - 0.2
0.2 - 0.3
0.3 - 0.5
0.5 - 0.7
0.7 - 0.9
0.9 - 1.2
1.3 - 1.8
Lee Vining
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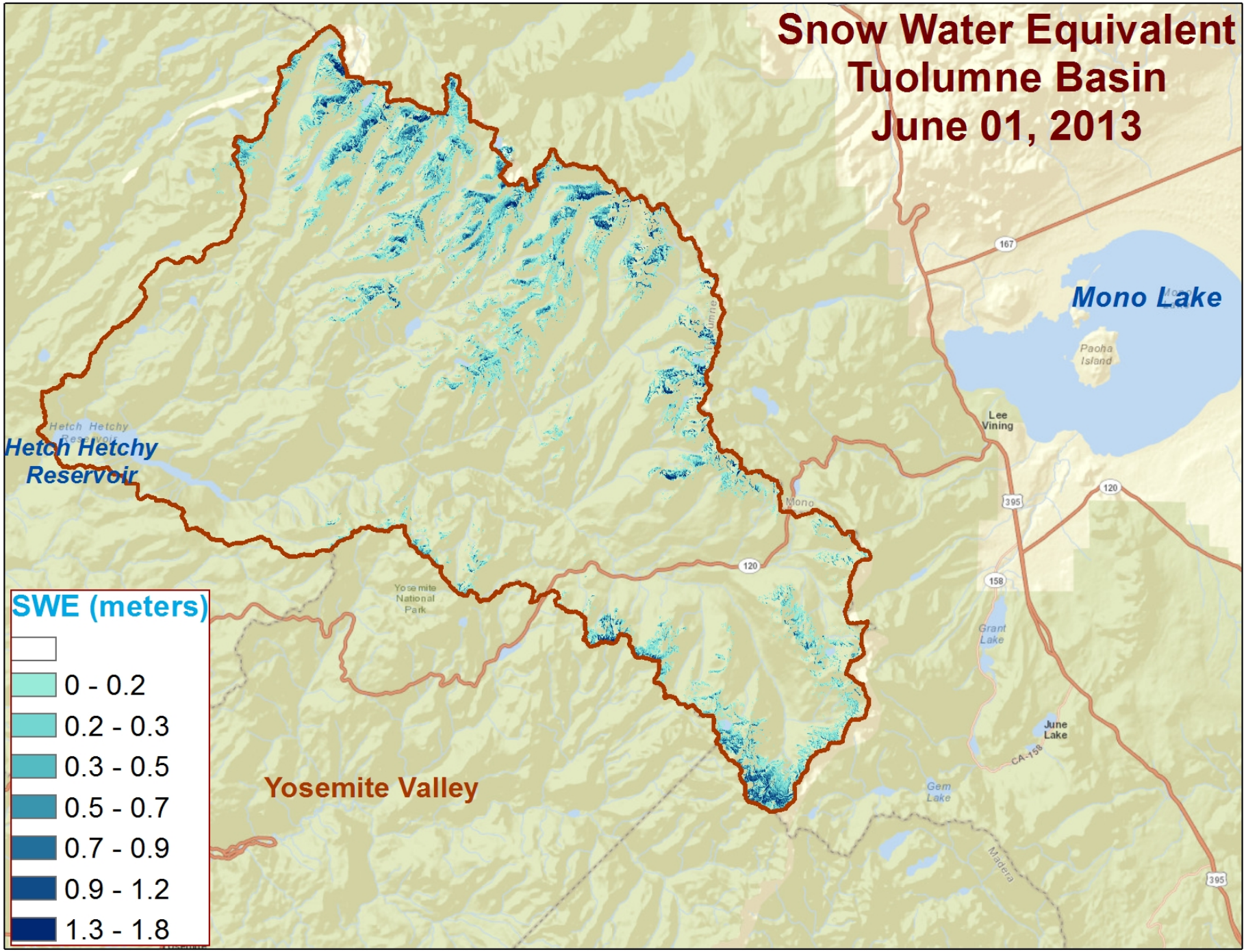
Snow Water Equivalent
Tuolumne Basin
June 01, 2013
Mono Lake
Hetch Hetchy Reservoir
Yosemite Valley
SWE (meters)
0 - 0.2
0.2 - 0.3
0.3 - 0.5
0.5 - 0.7
0.7 - 0.9
0.9 - 1.2
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Lee Vining
June Lake
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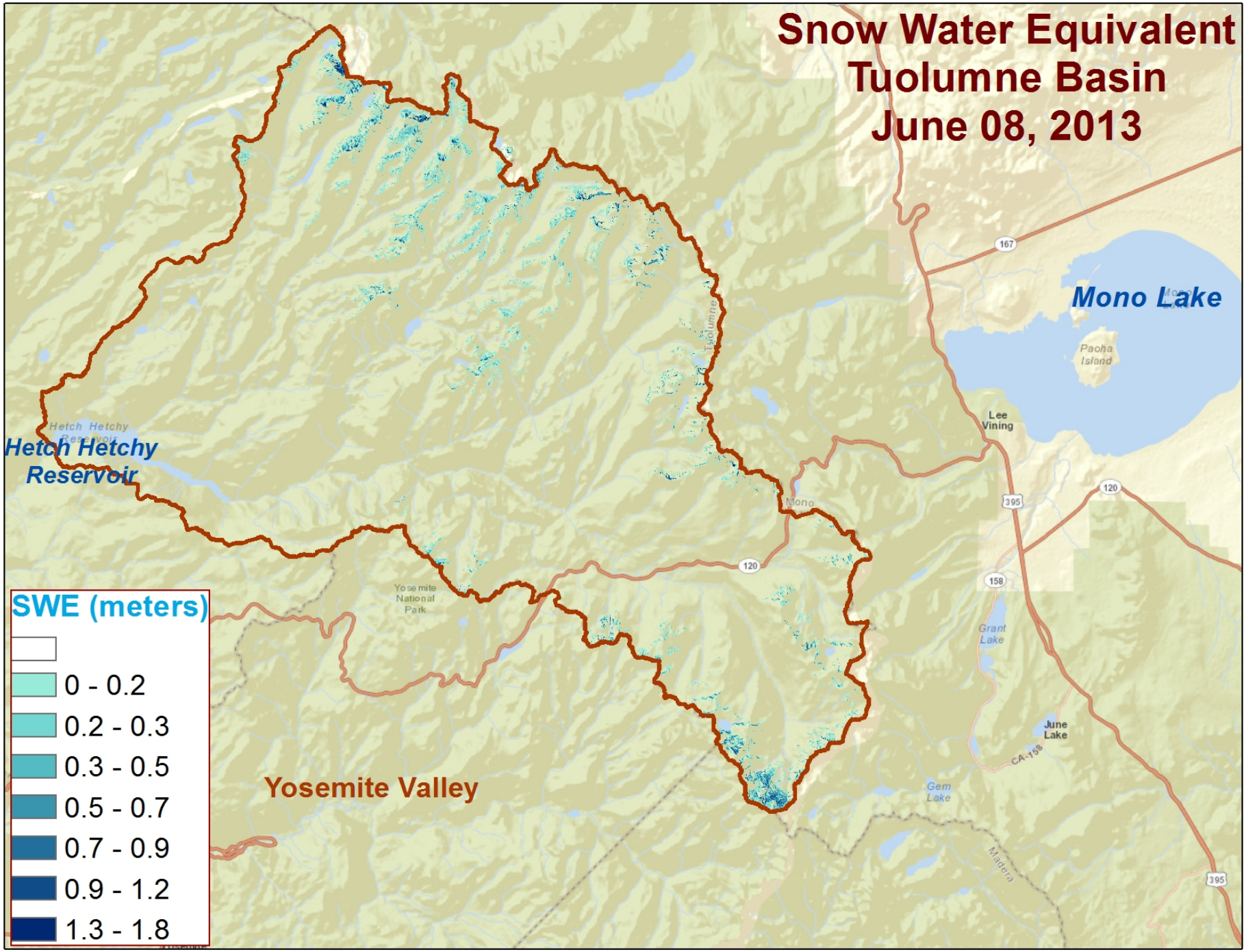
Snow Water Equivalent
Tuolumne Basin
June 08, 2013
Mono Lake
Hetch Hetchy Reservoir
Yosemite Valley
SWE (meters)
0 - 0.2
0.2 - 0.3
0.3 - 0.5
0.5 - 0.7
0.7 - 0.9
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Lee Vining
June Lake
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Yosemite National Park
Mono
Tuolumne
Madera
167
120
395
158
CA-158

What we just saw

- Across April 3 to June 8, 2013 we watched the complete time variation of the spatial distribution of snow water equivalent across the Tuolumne Basin at 1.5 m spatial resolution
- We saw the snowpack water volume drop from 218000 acre-feet to 15144 acre-feet, revealed on a weekly basis.
- That's enough water to supply more than 200,000 families of four for a year, transitioned from snowpack to ready to use.

All of this in < 24 hrs

The core of ASO is the supercomputing data analysis

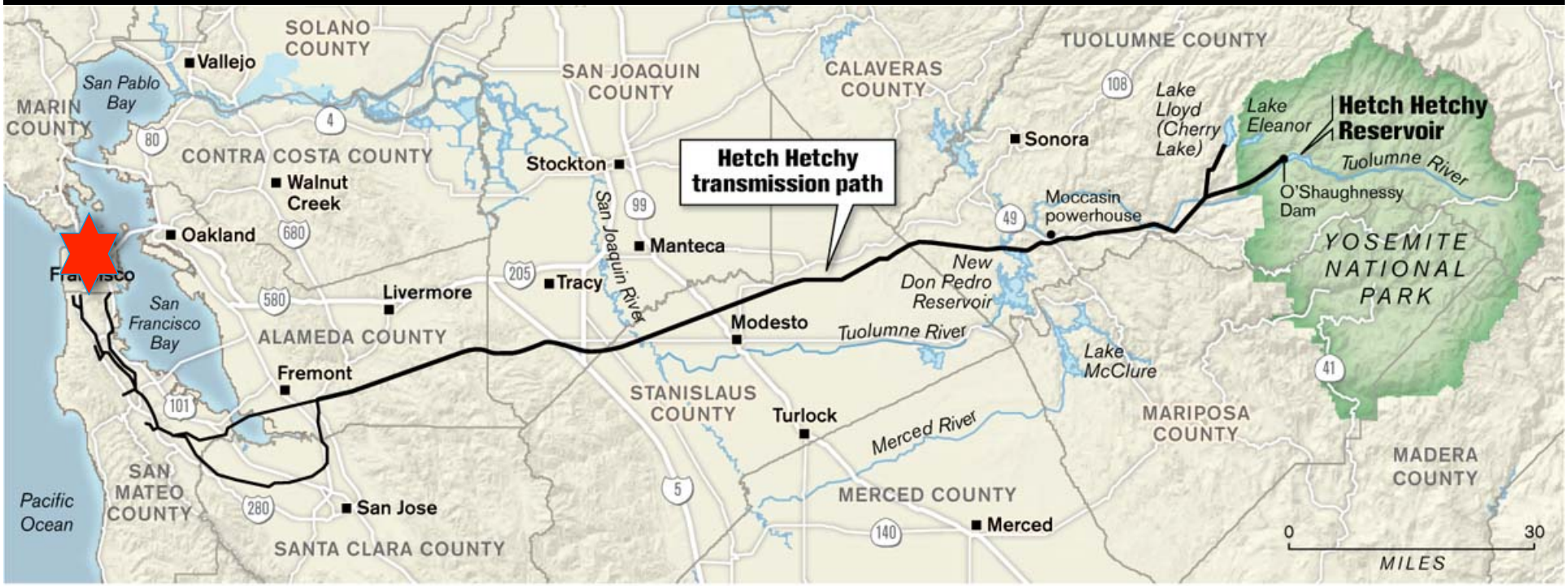
Applications of ASO to water management

Bruce McGurk, McGurk Associates

Hetch Hetchy Regional Water System

Rain-Dominated

Snow-Dominated



Sources: ESRI, TeleAtlas, USGS

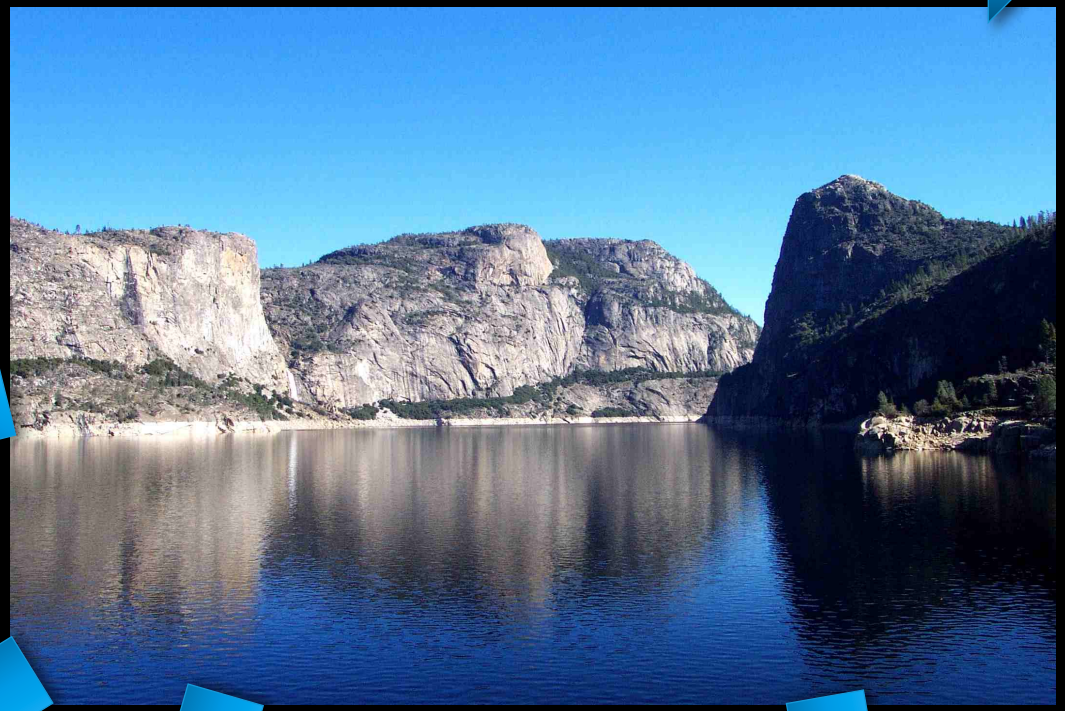
TODD TRUMBULL / *The Chronicle*

Reservoir Operations – Spill & Releases

May 1991 – 2 weeks of water left

Reservoir Operations

Time



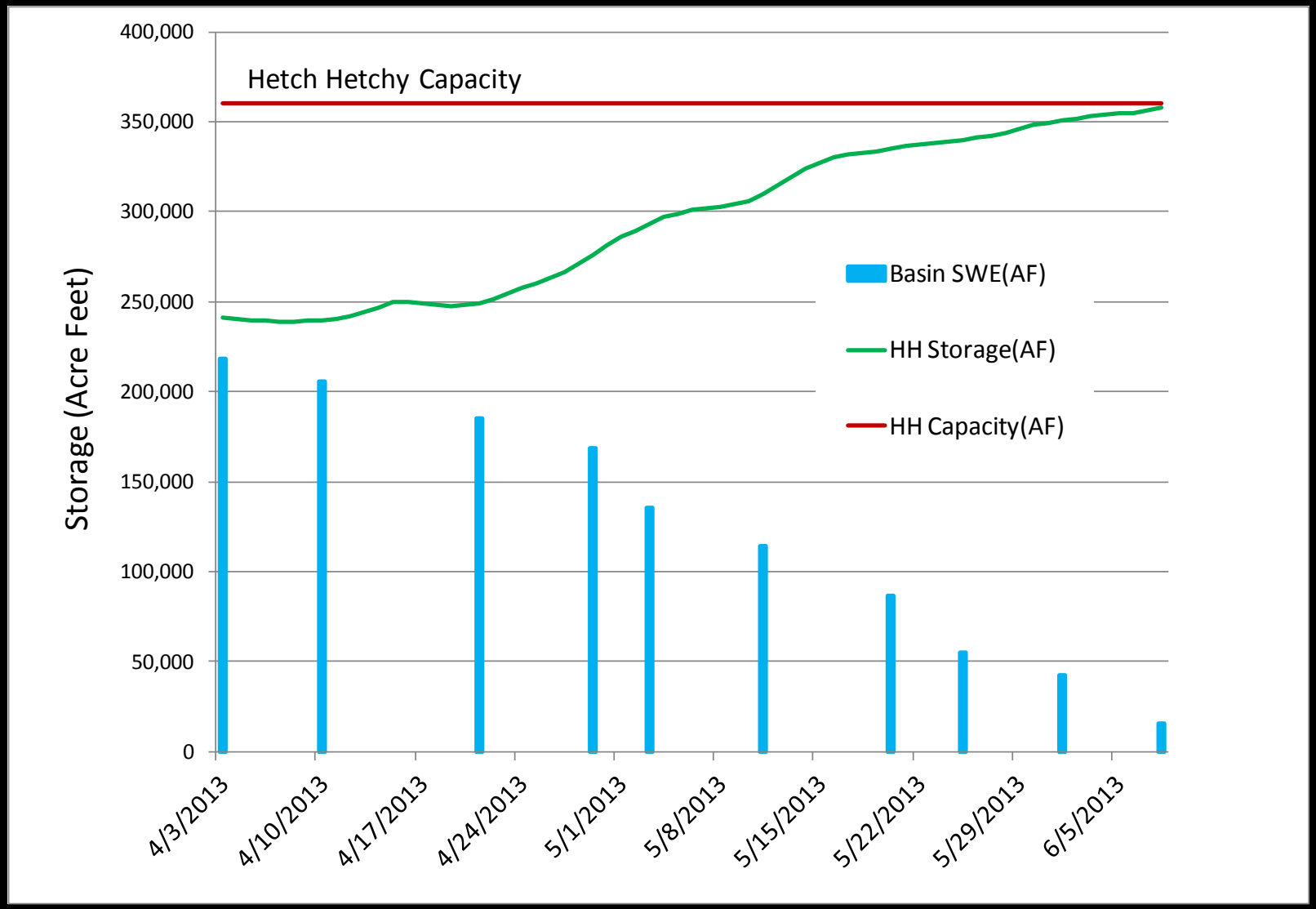
Snowmelt Inflow

Streamflow

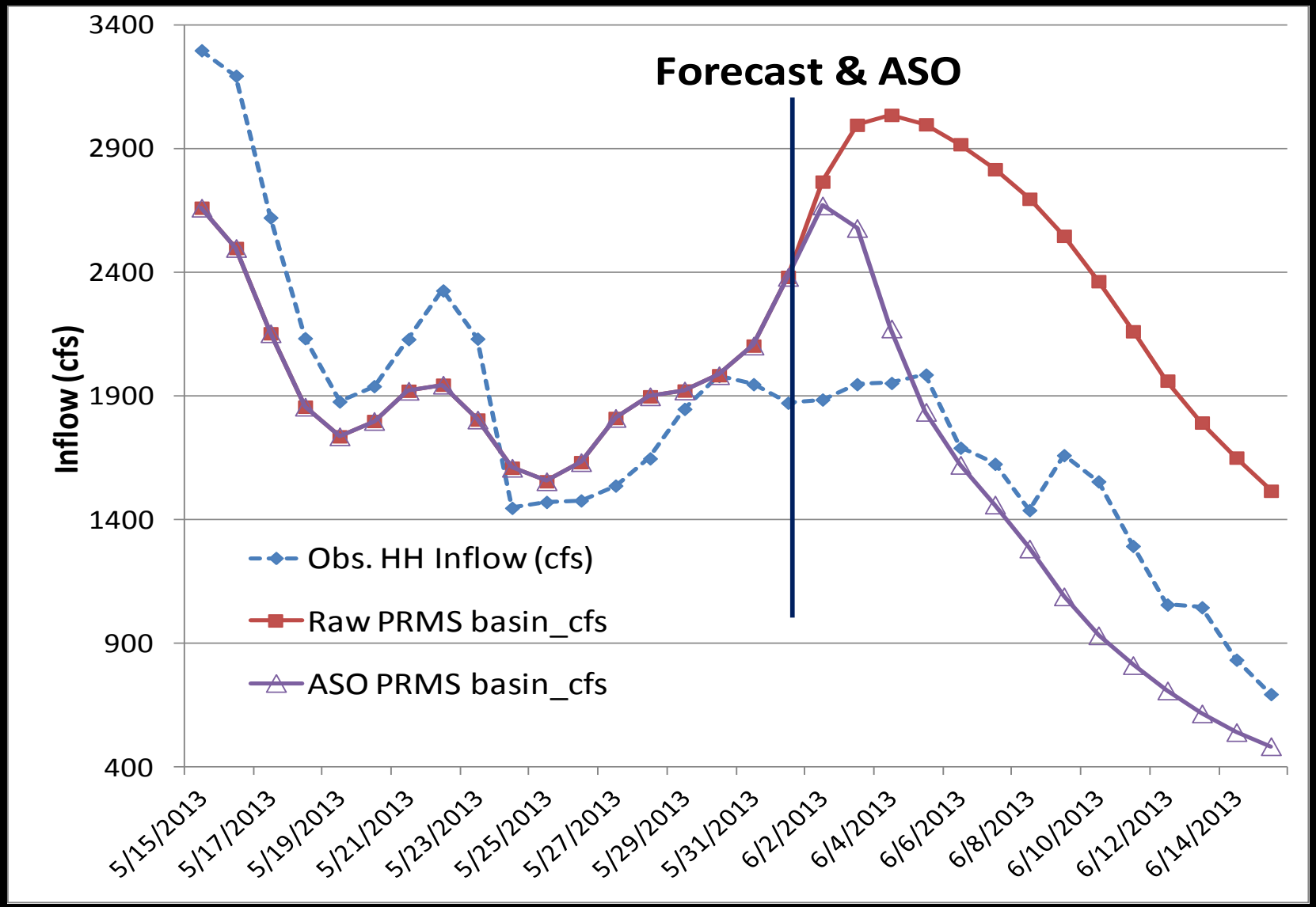
Power Generation

Water Supply

ASO Results and Reservoir Fill



Forecast corrected by ASO results



ASO Improves Reservoir Operations

- With ASO results and multiple forecast models, Hetchy Hetchy operations were optimized
- The reservoir reached capacity, ecological releases were made, and $3.9 million of hydropower was generated
- Detailed maps of SWE were produced in near real-time, allowing improved management and new science

Understanding Mountain Hydrology with ASO

Jessica Lundquist
Associate Professor
Civil and Environmental Engineering
University of Washington

Sierra Hydrologic Cycle

Snow on the ground

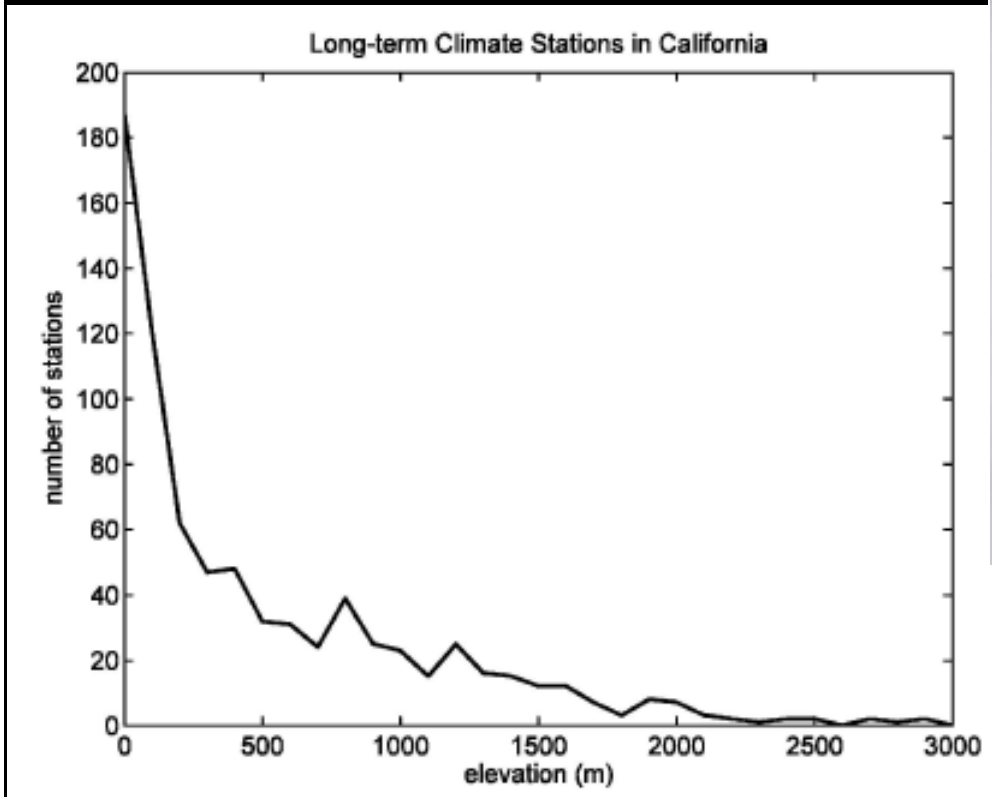
Precipitation

Snow Melts

Streamflow

Precipitation = Hard to know

- Harsh weather
- Power limitations
- Difficult access



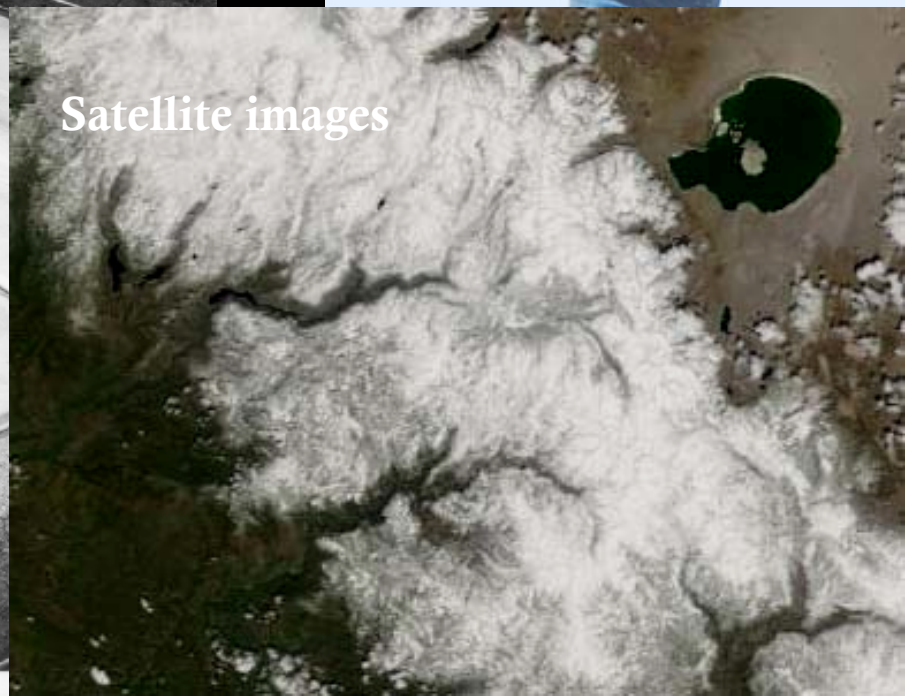
Graphic from Lundquist et al. 2003

Onion Creek HMT station April 2011
(photo courtesy of Nic Wayand)

Snow is hard to know: point measurements and snow cover

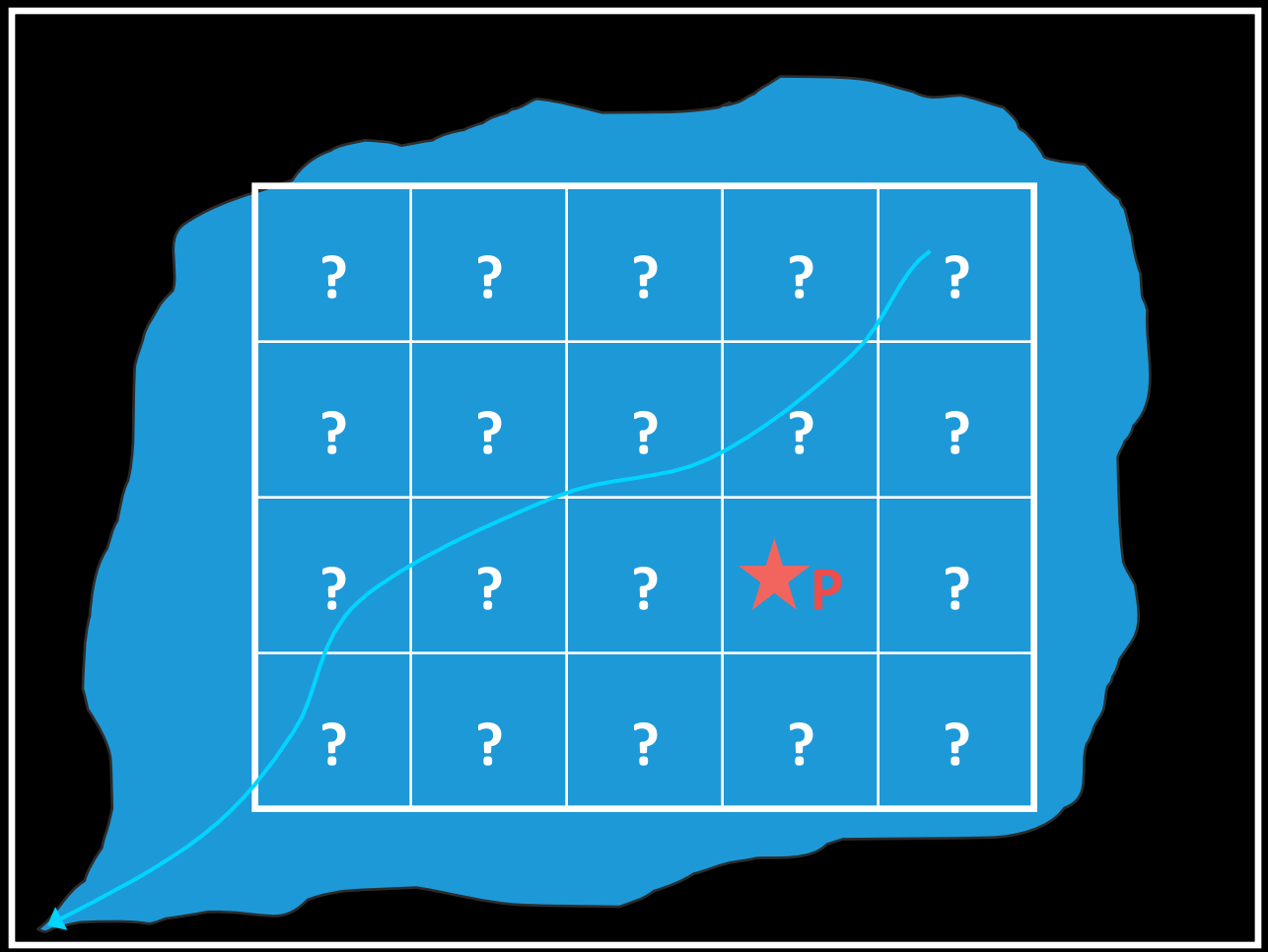
Snow courses

Snow pillows

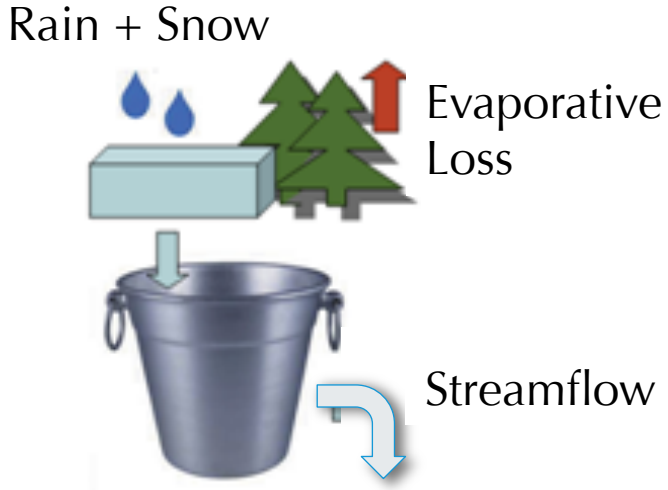


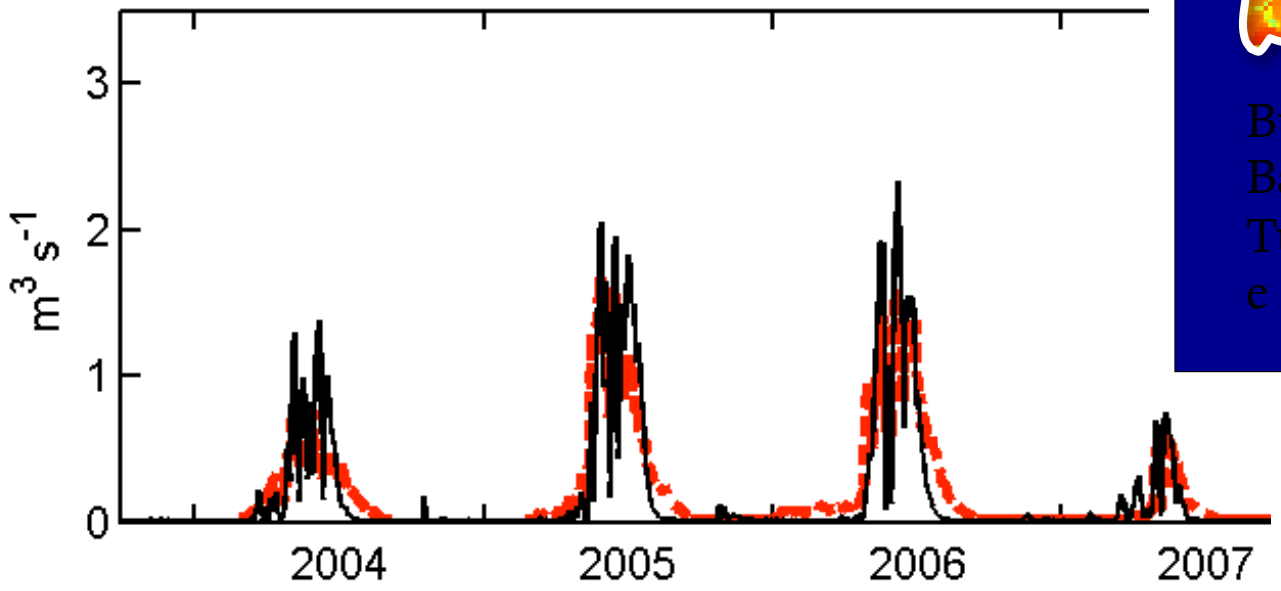
Satellite images

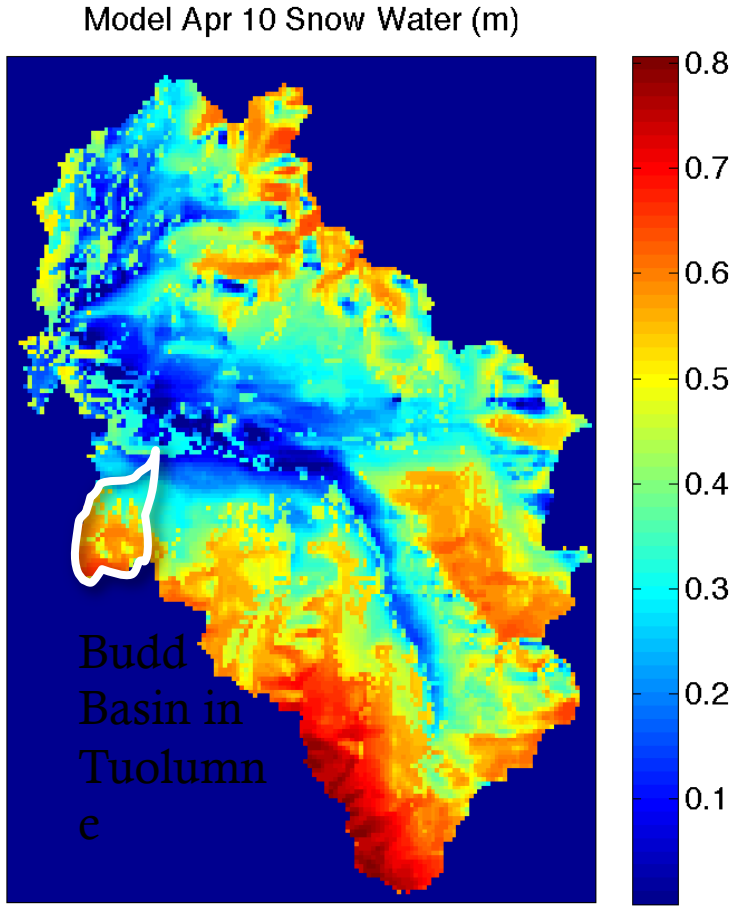
We measure precipitation at a point and map to the rest of the watershed



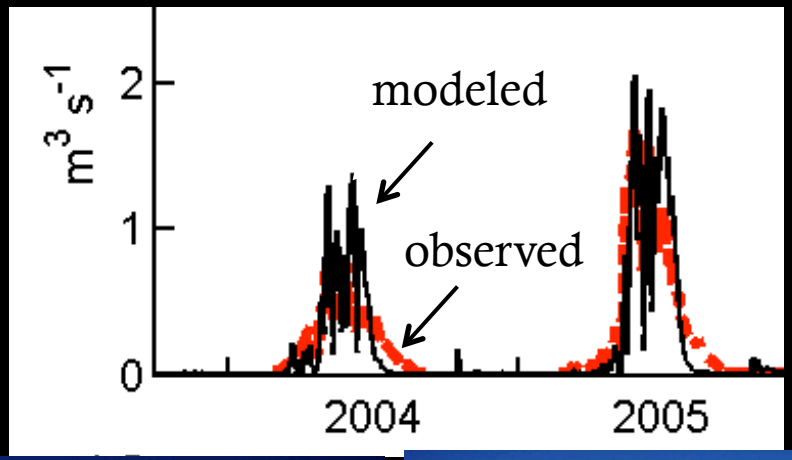
The sum of rain and snow over an entire basin becomes streamflow



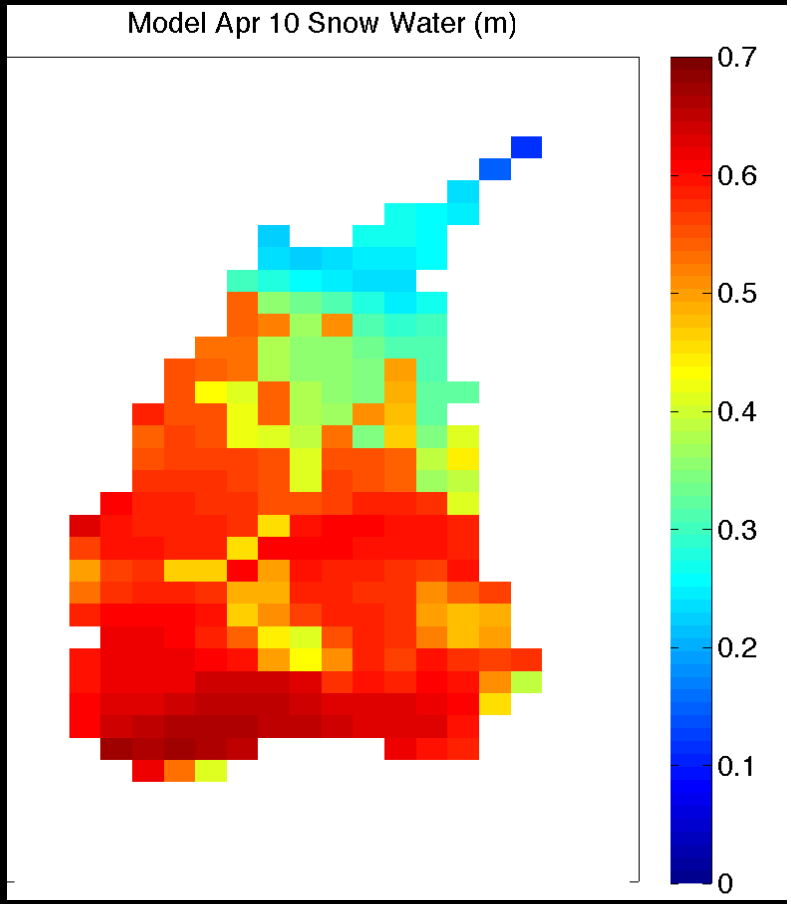


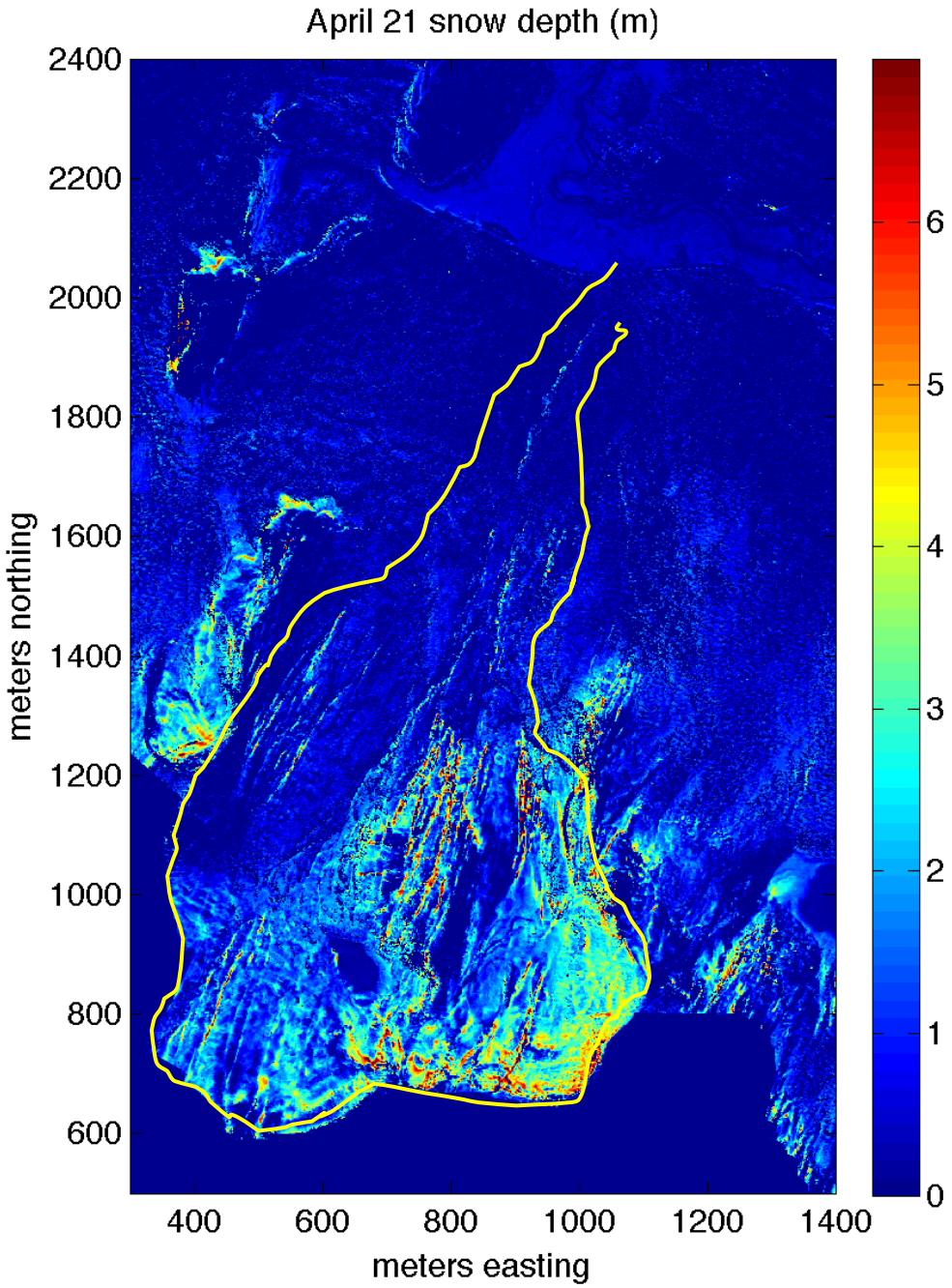


Model does not represent variability we know is in nature and misses late-season snow melt critical to meadow plants

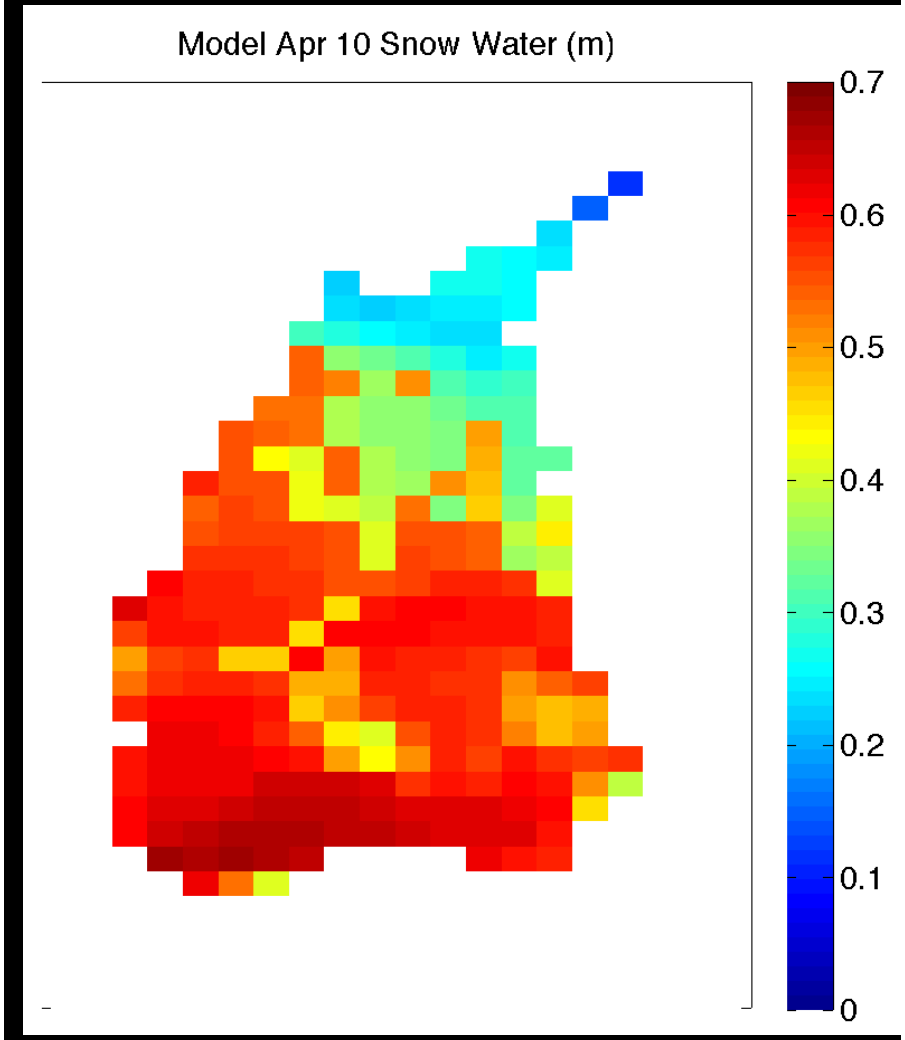


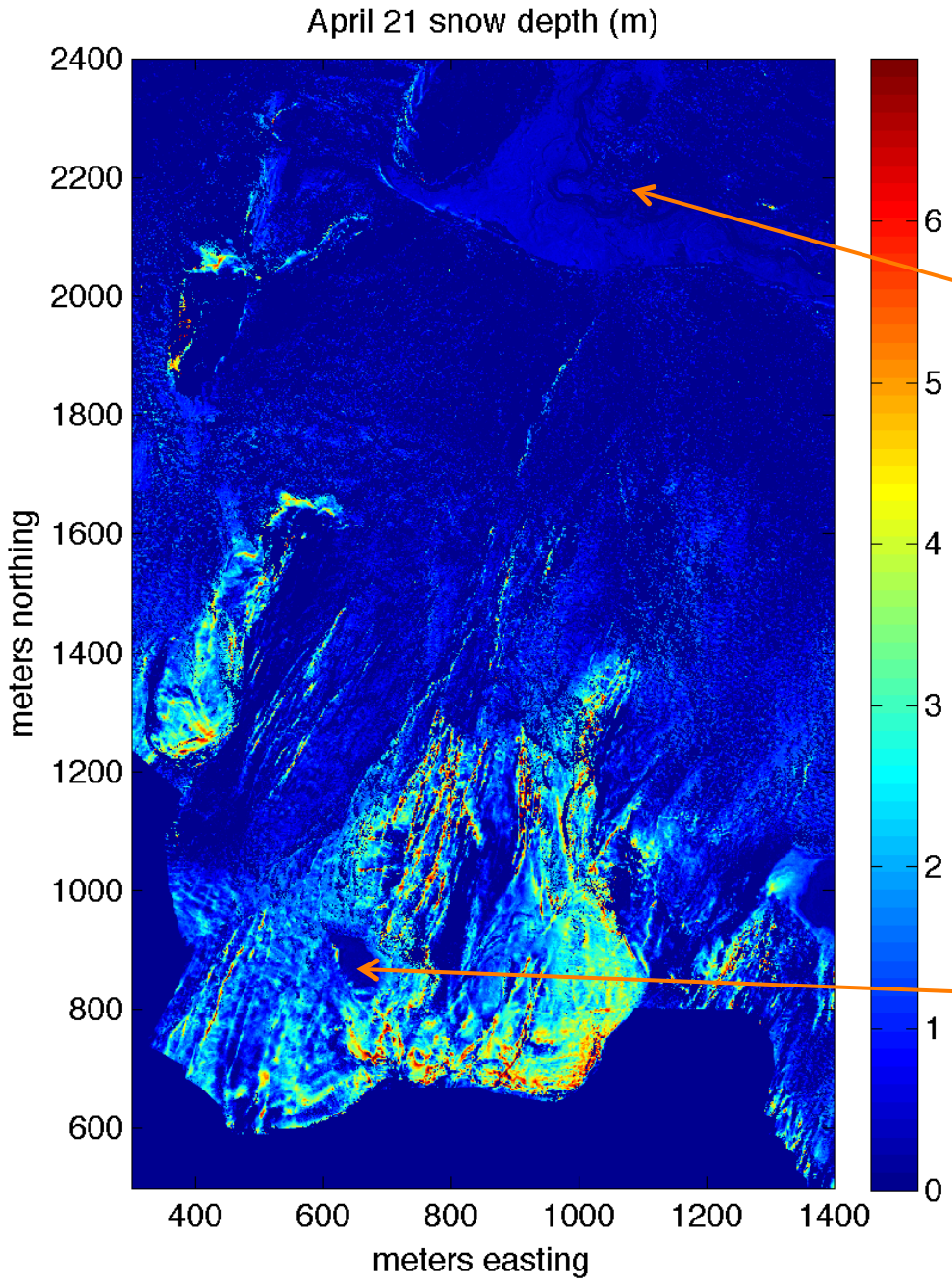
Model: Gradual increase in snow with elevation

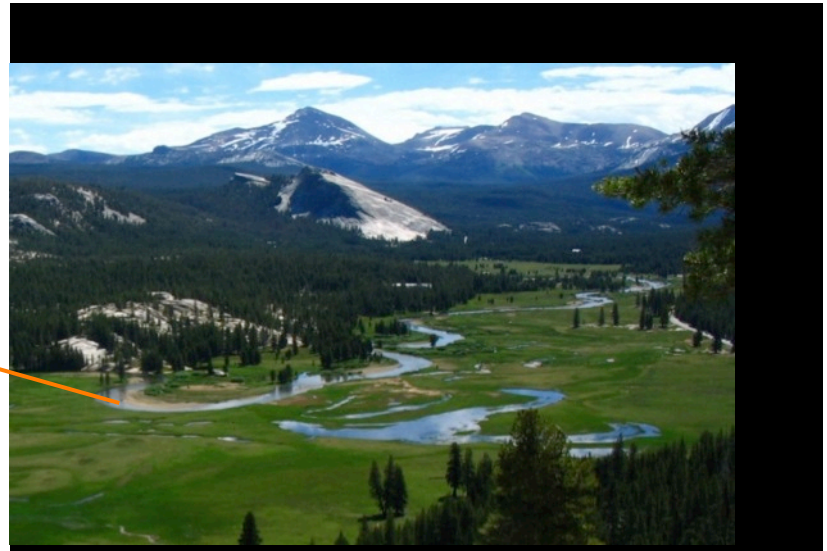




LiDAR data show variability and give the model direction to improve



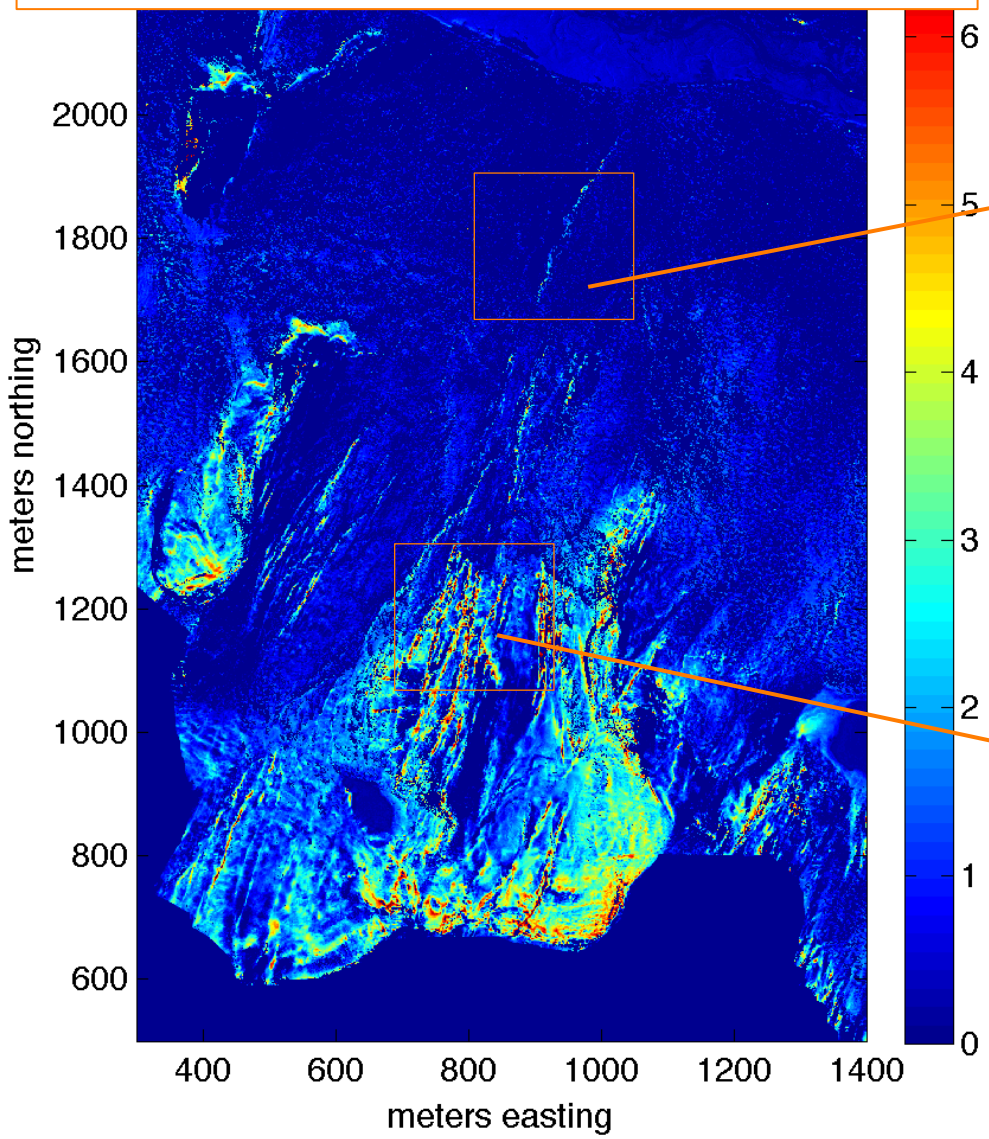


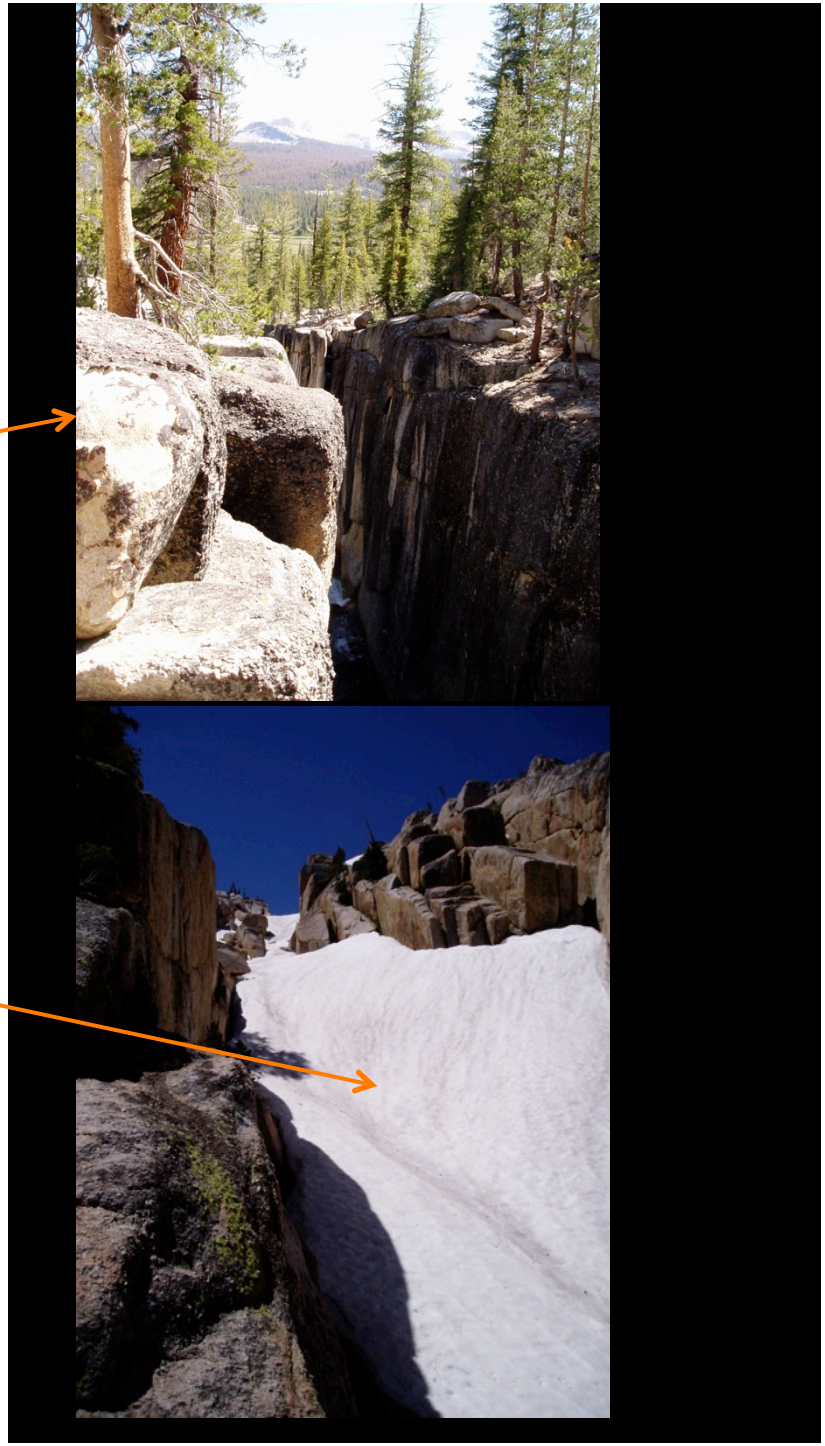


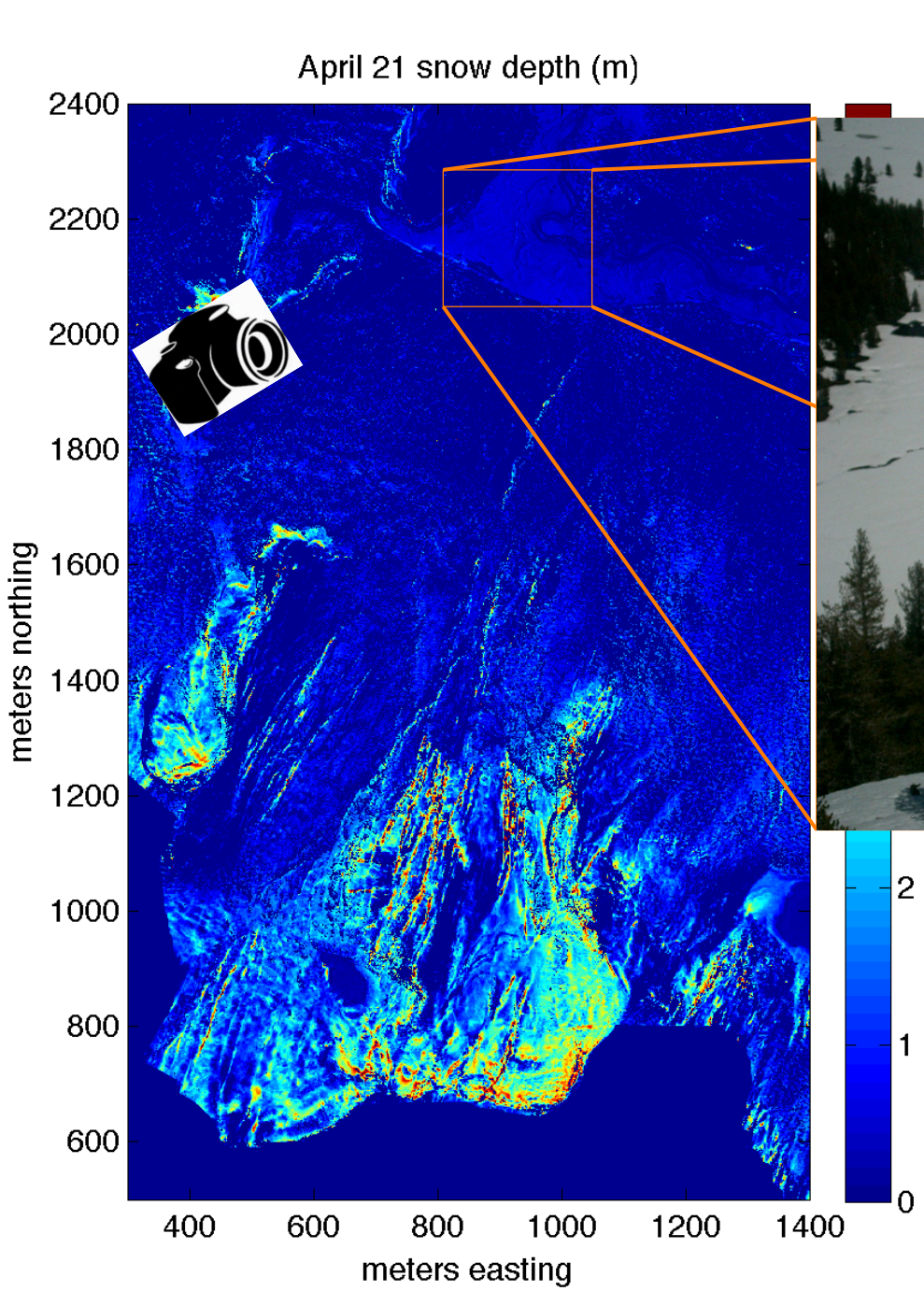
Tuolumne Meadows

Budd Lake

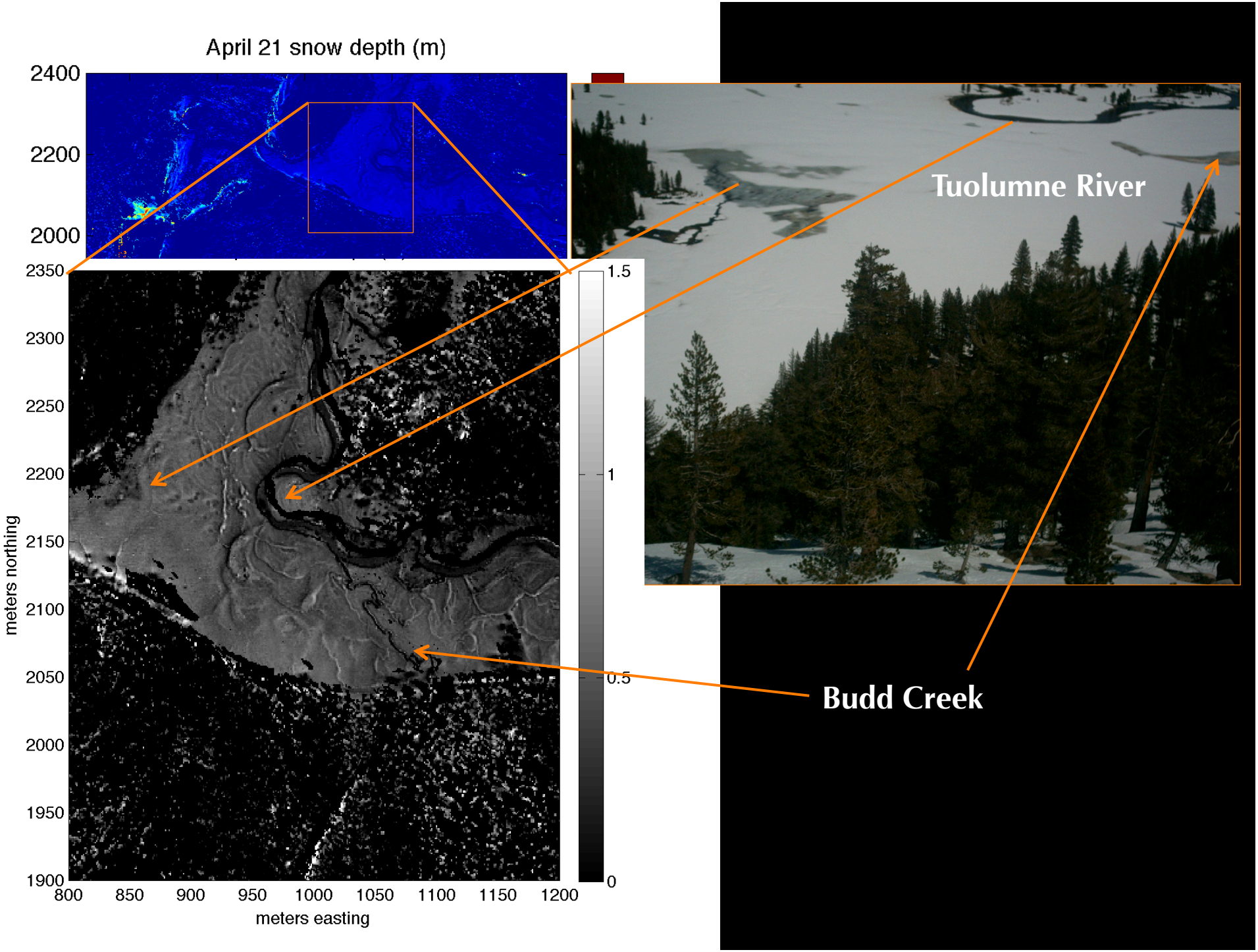
Landscape is full of fissures that fill with snow



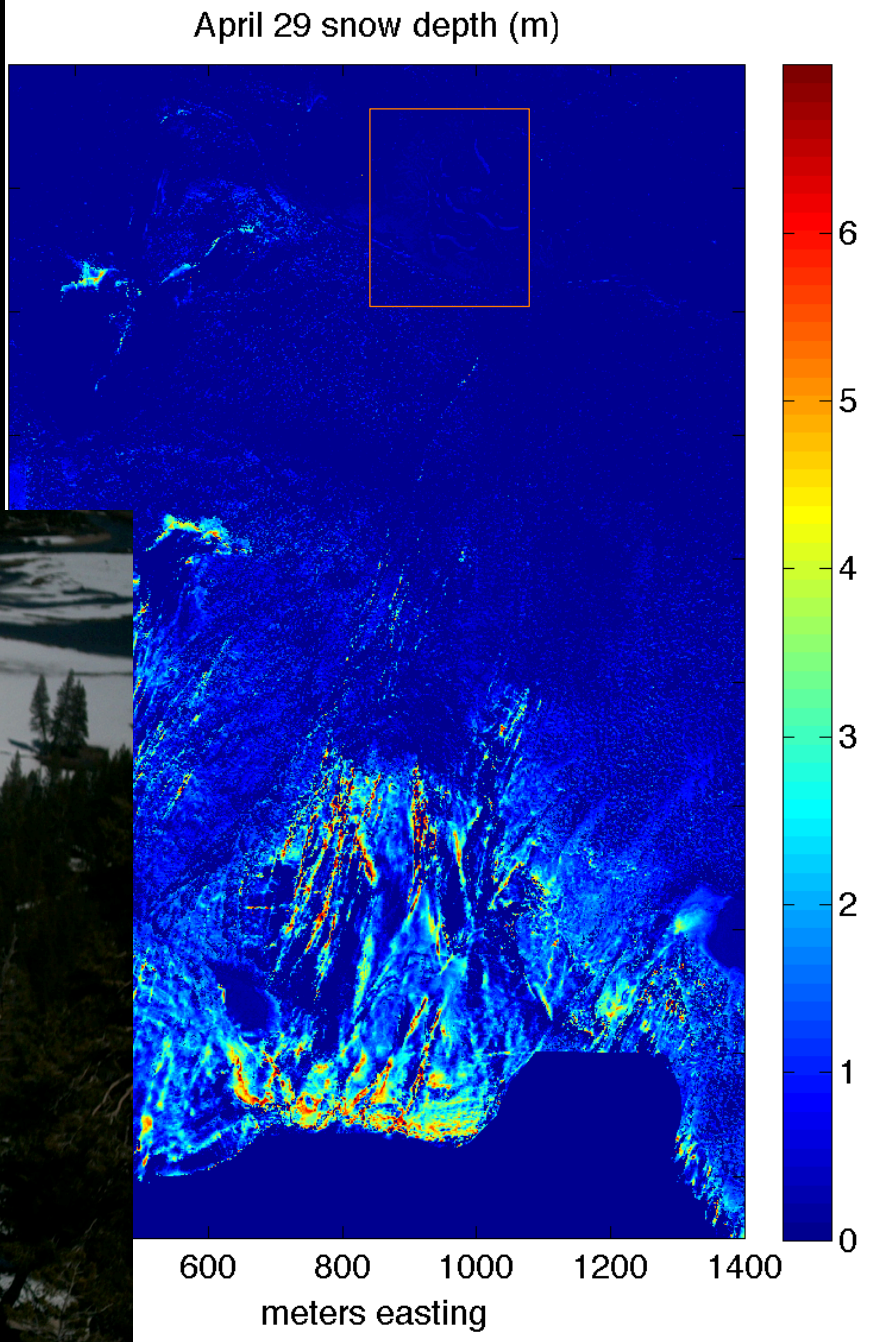




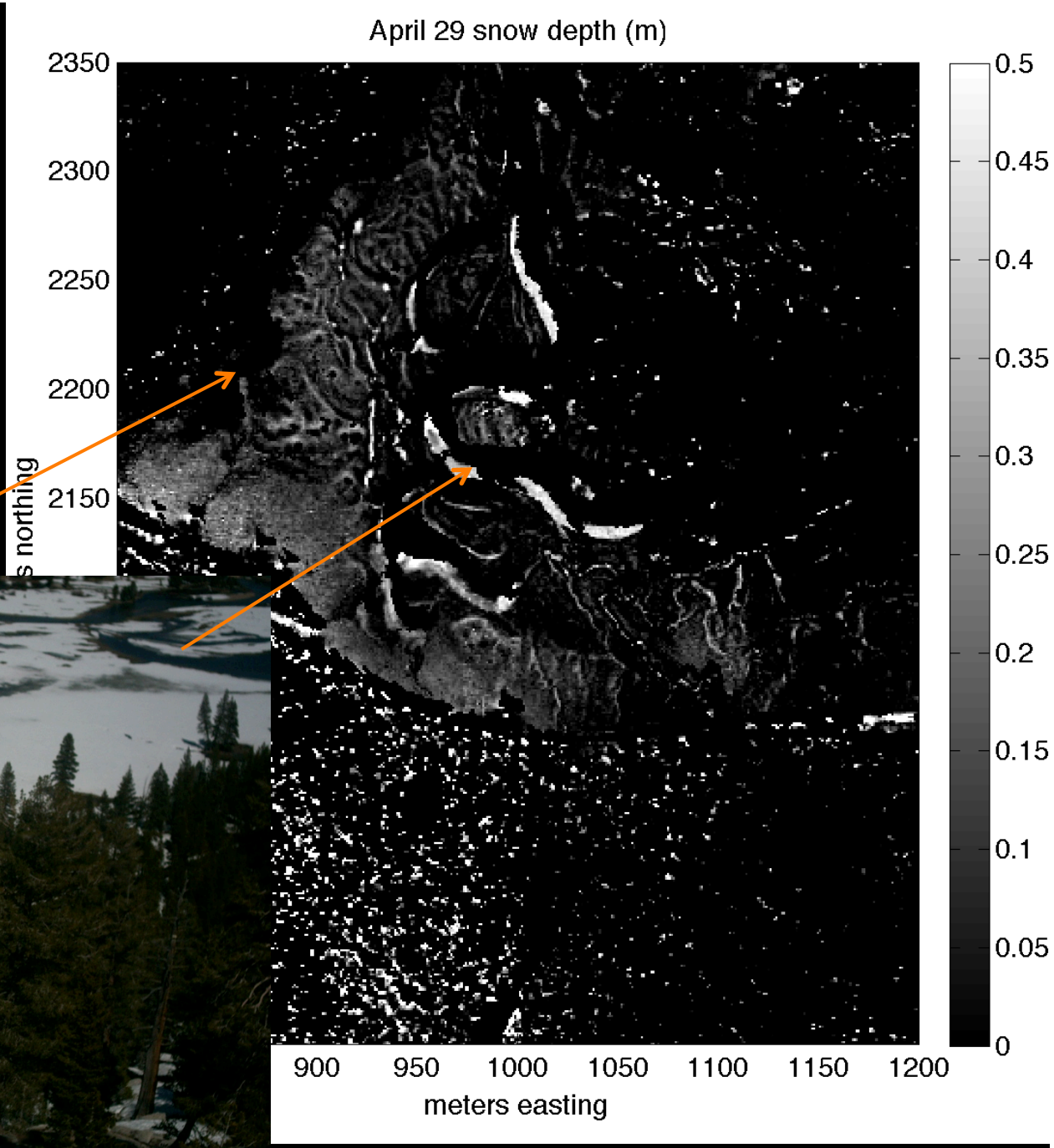
April 21 photo from Marmot Dome


April 21 snow depth (m)
2400
2200
2000
2350
2300
2250
2200
2150
2100
2050
2000
1950
1900
meters northing
800
850
900
950
1000
1050
1100
1150
1200
meters easting
1.5
1
0.5
0
Tuolumne River
Budd Creek

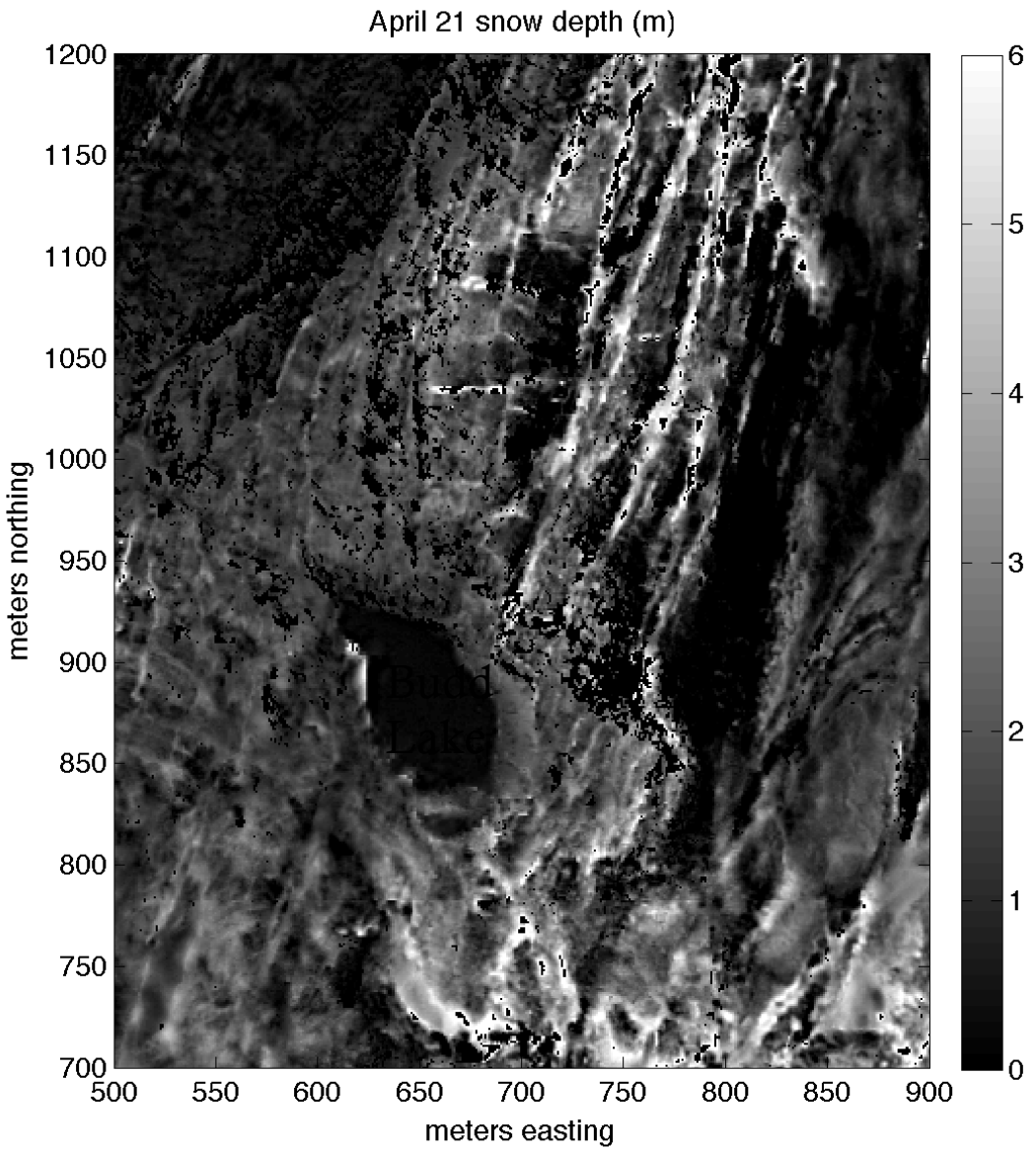
One week later, meadow snow is disappearing



LiDAR sees the forming lakes and last piles of snow



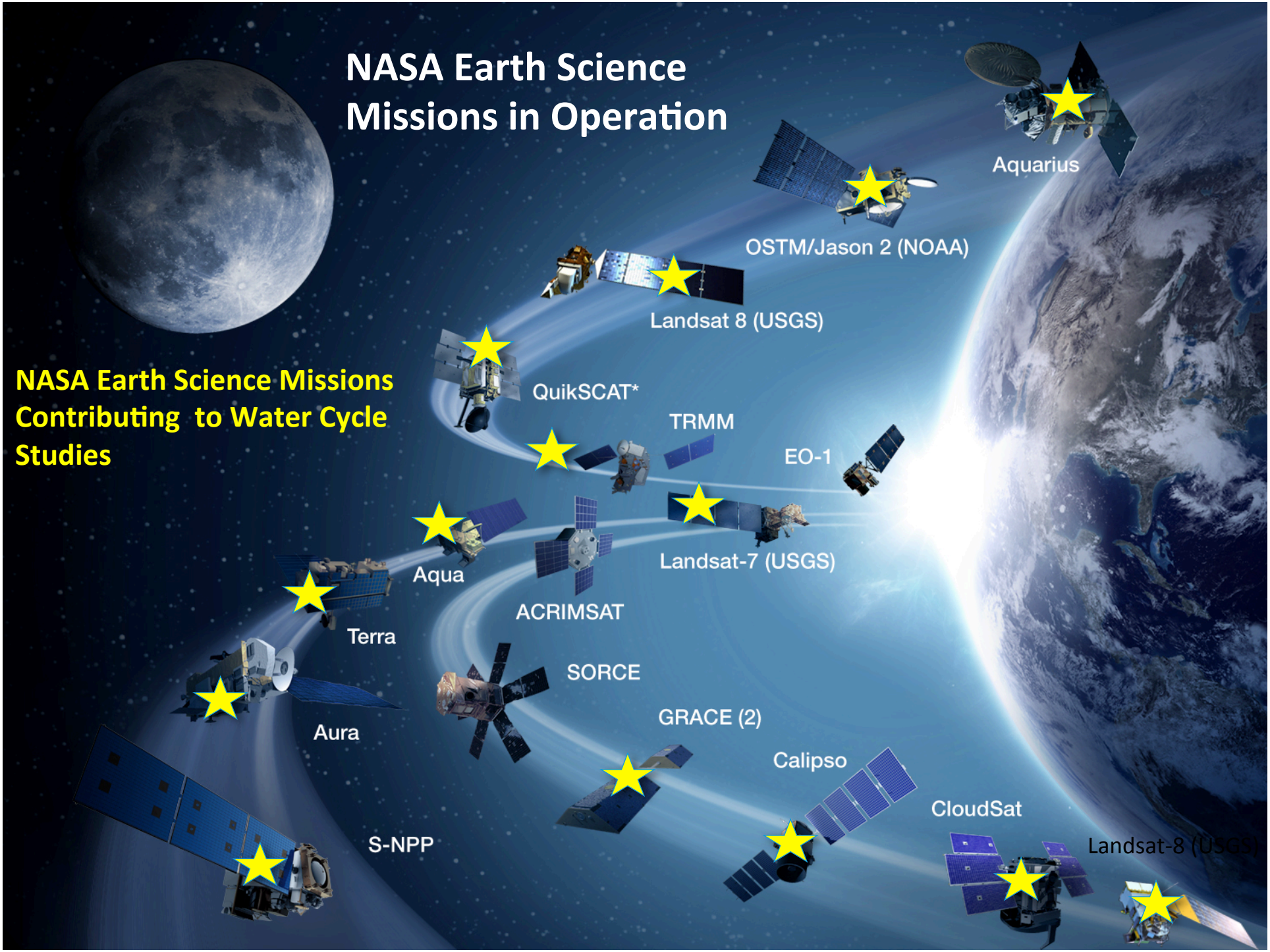
New observations = new science



- We're just beginning to analyze the data
- We see snow in space and time in a manner never possible before
- Many applications to be discovered

Airborne Snow Observatory (ASO) – NASA perspective

Bradley Doorn, Water Resources Program Manager,
NASA Earth Science Division, Applied Sciences Program

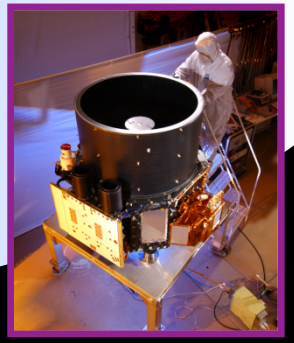

NASA Earth Science
Missions in Operation
NASA Earth Science Missions
Contributing to Water Cycle
Studies
Aquarius
OSTM/Jason 2 (NOAA)
Landsat 8 (USGS)
QuikSCAT*
TRMM
EO-1
Landsat-7 (USGS)
Aqua
ACRIMSAT
Terra
SORCE
Aura
GRACE (2)
Calipso
CloudSat
S-NPP
Landsat-8 (USGS)

New and Upcoming Freshwater Observing Satellite Missions

Landsat 8

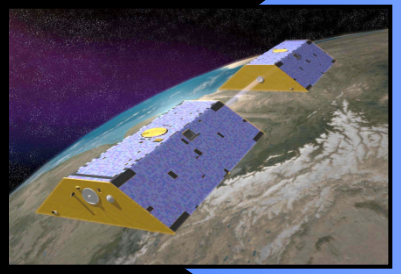
Global Precipitation Measurement

Soil Moisture Active-Passive (SMAP)
2014
Soil Moist., Freeze/Thaw



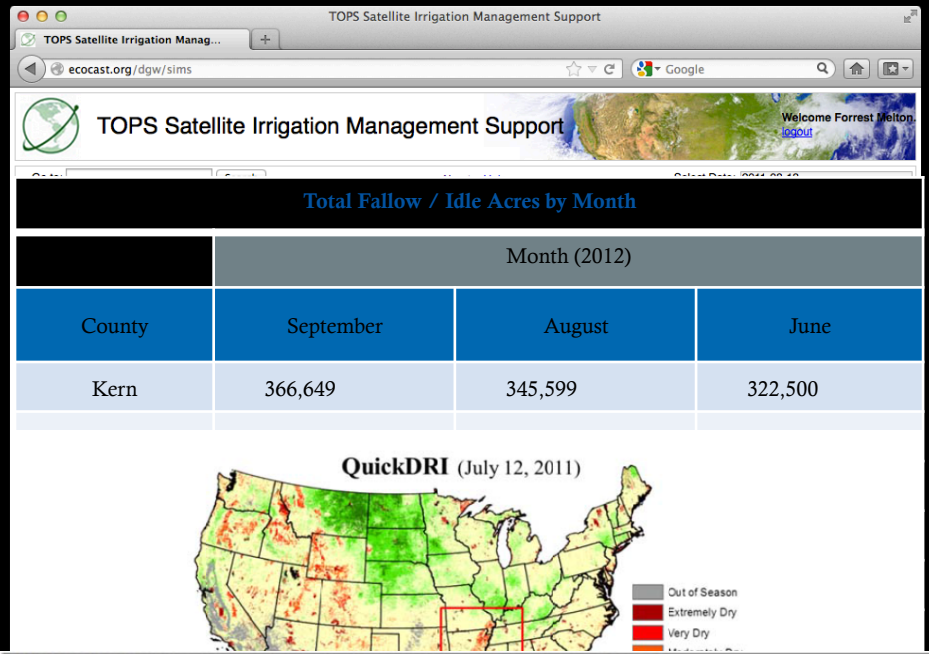
Ice, Cloud,and land Elevation Satellite

Cyclone Global Navigation Satellite System (CYGNSS)
2016



Gravity Recovery and Climate Experiment (GRACE) Follow-On

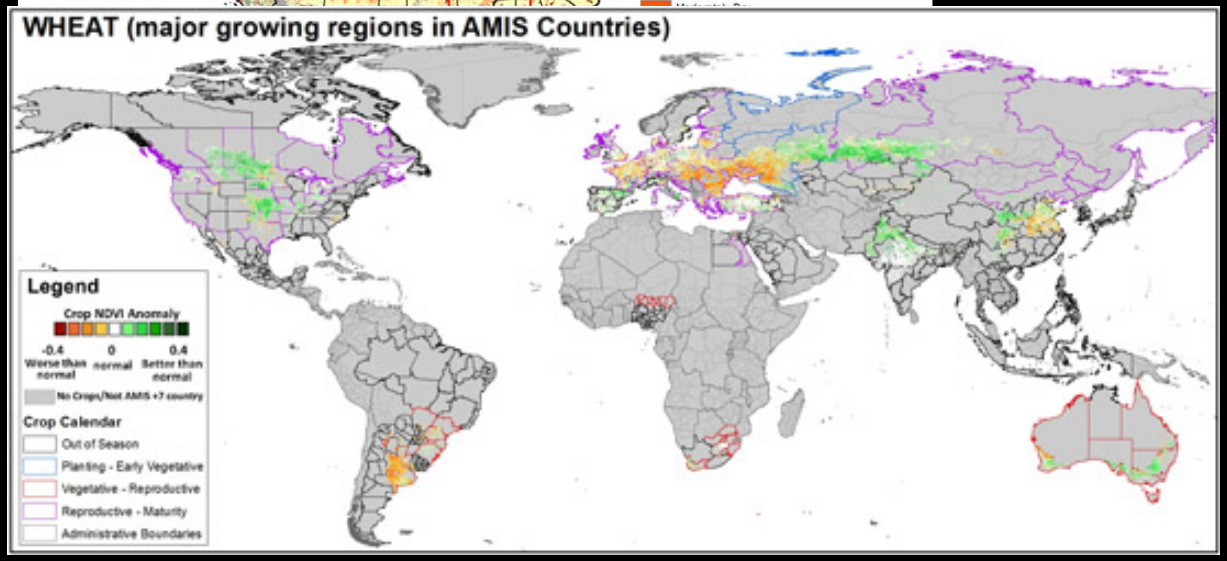
Examples of water resource applications using NASA satellite measurements



Irrigation Management
(NASA Ames, CDWR)

Agricultural mapping to support water management
(NOAA, USDA, USGS, CDWR)

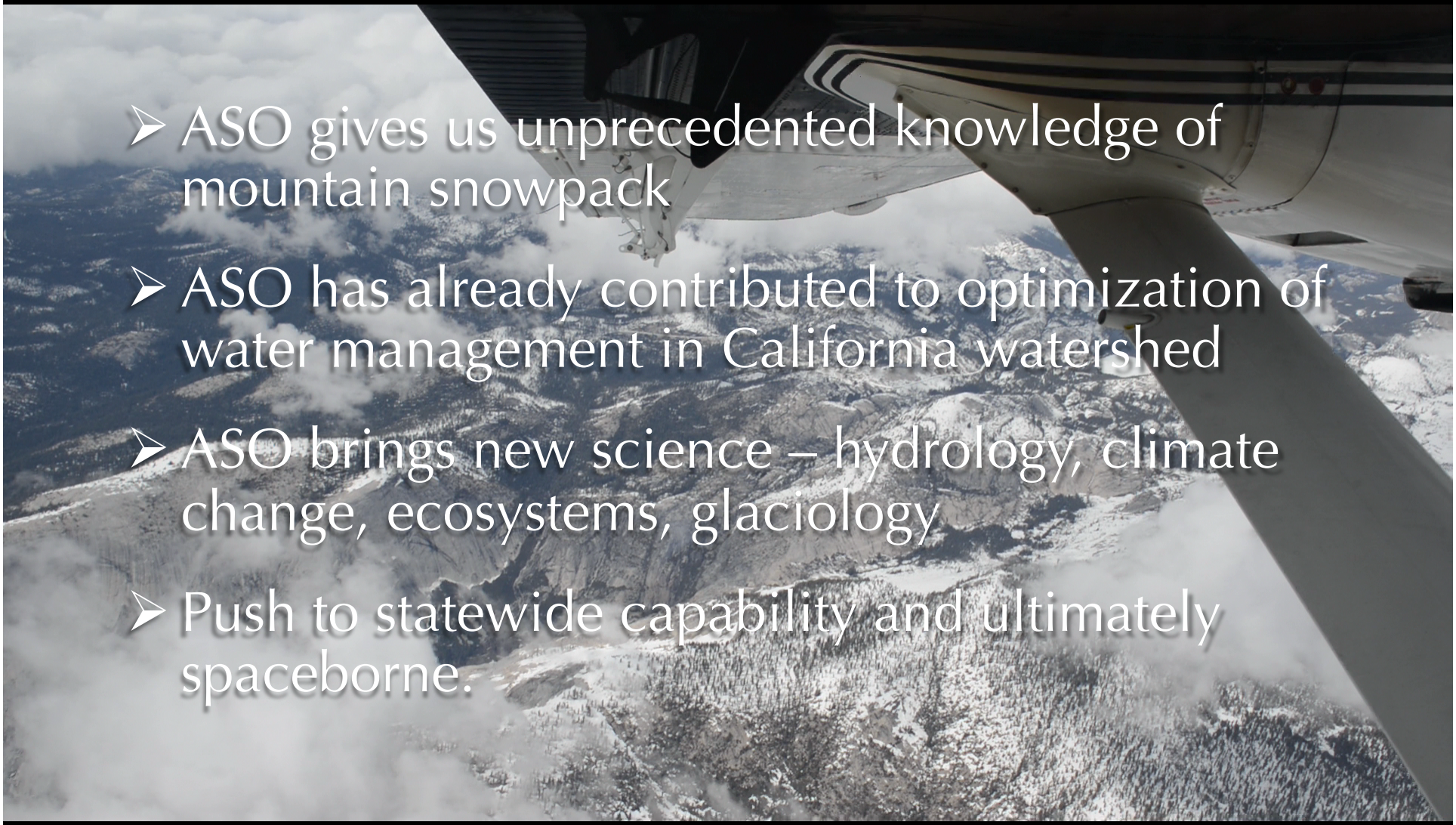
National drought forecasting and management
(NOAA, U.S. Drought Monitor)



Global Crop Monitoring
(USDA, G-20, 28 participating countries)

Other applications include ***dust storm and flood forecasting, ground water measurements, and more***

Summary



- ASO gives us unprecedented knowledge of mountain snowpack
- ASO has already contributed to optimization of water management in California watershed
- ASO brings new science – hydrology, climate change, ecosystems, glaciology
- Push to statewide capability and ultimately spaceborne.